



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2025): 5.20
www.agronomyjournals.com
2025; SP-8(9): 397-402
Received: 12-07-2025
Accepted: 18-08-2025

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Sustainable approaches in modern weed management: Challenges and Opportunities

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DOI: <https://www.doi.org/10.33545/2618060X.2025.v8.i9Se.3916>

Abstract

Weeds continue to remain a major constraint in agriculture, causing extensive yield losses, reducing produce quality, and increasing the cost of cultivation. In addition to competing with crops for vital resources like light, space, water, and nutrients, they also act as substitute hosts for diseases and insect pests. Globally, weeds are responsible for nearly one-third of the total losses caused by agricultural pests, with annual crop yield reductions in India alone estimated at more than 25 million tonnes. Over the years, weed science has evolved from simple manual and cultural practices to advanced methods involving herbicides, biological control, and mechanization. However, sole dependence on any one method has resulted in ecological and economic challenges, particularly the emergence of herbicide-resistant biotypes, shifts in weed flora, spread of invasive alien species, and persistence of parasitic weeds. Climate change has further complicated crop-weed interactions, demanding site-specific and adaptive solutions. Integrated Weed Management (IWM), which blends preventive, cultural, mechanical, chemical, and biological methods, has emerged as the most viable and sustainable strategy for the future. Recent technological innovations, such as remote sensing, drone-assisted herbicide application, artificial intelligence-based weed detection, nanotechnology-enabled formulations, and biotechnological tools like CRISPR for developing herbicide-tolerant crops, open new avenues for effective management. This review highlights the historical progress, current practices, emerging challenges, and future opportunities in weed science, underscoring the urgent need for eco-friendly, cost-effective, and farmer-centric solutions to safeguard global food security and environmental sustainability.

Keywords: Economic threshold level, herbicide resistance, integrated weed management, parasitic weeds

Introduction

Weeds have existed for ages, representing plants that are either not part of cultivated crops or are unintentionally grown alongside them in the primary field. These invasive plants not only coexist with crops but also compete for vital resources such as nutrients, space, sunlight, and water. This competition significantly impacts agricultural productivity, leading to considerable losses, as noted by Das (2008) [18]. Weeds are responsible for approximately one-third of the total damage caused by agricultural pests. Consequently, enhancing agricultural productivity in India must involve strategies to minimize losses due to weeds. Weeds are the most significant and widespread biological challenge to agricultural production systems, causing damage in both cultivated and uncultivated areas. They not only lower crop yields but also degrade the quality of produce and increase production costs. Weeds frequently act as substitute hosts for a variety of insect pests and illnesses, which can lower land value in addition to production and nutrient losses. In non-cropped areas, weeds can lead to health risks and a decline in biodiversity. Despite advancements in weed science research and extension efforts, Indian farmers continue to face substantial crop yield losses due to weed interference. The impact of weeds on agricultural crops varies depending on factors such as the ecological conditions in which crops are grown, hydrology, land topography, environmental interactions, crop establishment methods, and cultural practices employed. Crop loss estimates are often inaccurate due to the lack of comprehensive scientific assessments.

However, even the most conservative estimate of a 10% loss translates to approximately 25 million tons of food grains, which is currently valued at around USD 13 billion (Yaduraju, 2012)^[52]. Weed control involves managing weed infestations to ensure crops can be cultivated profitably and human activities conducted effectively. The primary goal of weed control is to regulate vegetation on land and in water bodies to promote the growth of plants beneficial to humans while suppressing undesirable ones. It is not about indiscriminately targeting all plants but rather adopting selective measures. Weed eradication, which entails the complete removal of all live plant parts and seeds from a specific area, is an ambitious and costly process, often exceeding the value of the land itself. Additionally, total vegetation removal is unnecessary, as many plants provide ecological and practical benefits. However, eradication can be justified for harmful weeds such as *Cuscuta*, *Xanthium*, and *Lantana*, especially if tackled early when the weeds are still small and less widespread. The concept of weed management is increasingly emphasized over mere control. While weed control focuses on suppressing existing weeds, weed management takes a proactive, systemic approach to land use planning, aiming to prevent aggressive weed invasions and give crops a competitive edge. This integrated strategy, known as Integrated Weed Management (IWM), combines multiple methods preventive, cultural, chemical, and biological to maintain weed populations at levels that do not cause economic harm.

IWM is driven by several factors: the shift of minor weed species into dominant roles due to repeated reliance on the same control methods, growing concerns over the environmental and health impacts of pesticides, and the emergence of herbicide-resistant weeds. It is a decision-making process that involves determining the optimal timing for control measures using critical thresholds and selecting the most effective combination of techniques to achieve maximum control and profitability.

Advances in Modern Weed Management Practices

Substantial progress has been achieved in weed control since the advent of modern weed science despite persistent challenges. These improvements have enabled significant crop yield enhancement. With a rising global population and shrinking arable land, future weed management research must evolve continuously to secure food production for coming generations (Das, 2008)^[18].

Herbicide Adoption and Social Drivers

The widespread adoption of herbicides, especially in developed regions, has been primarily influenced by social factors such as labour reduction needs and rural demographic shifts away from farming. Herbicides offer multiple advantages including better weed suppression, earlier crop planting, reduced tillage, and lower production costs. Nonetheless, the development of herbicide resistance has emerged as a severe limitation, as evident from the case of isoproturon-resistant *Phalaris minor* in Punjab and Haryana, India, which persisted until alternative herbicides were formulated (Yaduraju *et al.*, 2012)^[52].

Categorization of Weed Management Methods

Weed management strategies generally fall into five categories that collectively address social, cultural, environmental, and economic concerns: Preventive, cultural, mechanical, biological, and chemical techniques.

Preventive Strategies

Prevention is paramount, focusing on restricting weed spread.

Common dissemination pathways include contaminated seeds, seed or plant parts moved via machinery, irrigation water, livestock, and organic inputs such as manure or compost. Successful prevention programs are often community-driven, emphasizing certified seed use and legal enforcement (Walker, 1995)^[50].

Cultural Control Methods

Cultural approaches exploit crop-weed competition and cropping system design to suppress weeds. This includes selecting competitive crops and genotypes, crop rotation, cover cropping, and adjusting sowing date and spacing. Optimizing crop sowing dates can minimize weed emergence; increasing seed rates can improve crop competitiveness but may affect yield quality; closer crop spacing enhances weed suppression by limiting resource availability to weeds (Mohler, 1996; Sindhu *et al.*, 2013)^[36, 45].

Certain crop genotypes, characterized by rapid emergence and canopy closure, provide competitive advantages, varying by environmental context. Allelopathic cultivars, capable of releasing weed-inhibiting compounds, offer another cultural tactic (Lemerle *et al.*, 2001; Olofsdotter, 2001)^[31, 39].

Fertilization Practices

Fertility management plays a critical role in crop-weed dynamics. Optimizing nutrient placement, especially nitrogen, favors crop uptake and limits nutrient availability to weeds, reducing their growth potential. Alterations in application timing and fertilizer types can influence nutrient competition. The use of nitrification inhibitors and organic amendments further modulate these interactions and affect weed germination (Kirkland and Beckie, 1998; Karssen and Hillhorst, 1992)^[30, 29].

Cover Crops and Intercropping

Cover crops improve weed control by shading out weed seeds and producing allelochemicals that inhibit germination. Off-season and smother cover crops vary in their weed suppression efficacy depending on species and weed seed characteristics, with small-seeded weeds typically more susceptible (Teasdale *et al.*, 1998; Bàrberi and Mazzoncini, 2001)^[48, 4]. Intercropping systems create heterogeneous resource environments, reducing light and space available to weeds and enhancing overall crop competitiveness. Such practices also foster ecological diversity and potential yield increase (Ballaré and Casal, 2000; Baumann *et al.*, 2000)^[3, 7].

Crop Rotation

Effective crop rotation disrupts weed life cycles by changing environmental conditions and selective pressures, thus reducing weed prevalence and vigor. Diversifying rotations lowers the dominance of weed species associated with specific crops (Karlen *et al.*, 1994; Liebman *et al.*, 1997)^[28, 32].

Mechanical Weed Control

Mechanical control includes physical removal methods such as hand weeding, hoeing, mowing, burning, and tillage. Effective particularly against annual and biennial weeds, it requires timely and frequent interventions. Mulching suppresses weeds by blocking sunlight, while soil solarization utilizes solar heat to reduce viable weed seeds. Tillage influences weed seed distribution and predator activity, with rotating tillage practices enhancing management efficacy. For example, alternating conventional and zero tillage proved superior for weed control in rice-wheat systems (Temperini *et al.*, 1998; Brust and House,

1988; Mishra and Singh, 2012) [49, 12, 35].

Chemical Control and Considerations

Chemical weed control necessitates careful selection of herbicides appropriate to weed species and timing to avoid crop damage. Environmental safety, residue impact on crops, persistence in soils, compatibility with other pesticides, and applicator health are critical concerns. The rise in herbicide-resistant weeds stresses the need for chemical methods to be integrated with other tactics rather than used exclusively (Hamill *et al.*, 2004) [24].

Biological Control

Biocontrol employs natural enemies parasites, pathogens, predators to reduce weed populations below economic damage thresholds. While mainly effective in non-cultivated areas for persistent weeds, certain pathogen applications, such as fungi targeting round-leaved mallow, have been successful in crop fields. Biological methods complement other management strategies in Integrated Weed Management (DeBach, 1964; Mortensen, 1988) [20, 37].

Integrated Weed Management (IWM)

IWM aims to manage weed competition within acceptable limits to preserve ecosystem balance and crop productivity. It combines preventive, cultural, mechanical, biological, and chemical approaches based on scientific monitoring and evaluation. Research shows integration of cultural and mechanical methods yields superior weed control efficiency compared to mono-strategies, particularly in organic cropping systems (Benaragama and Shirliffe, 2013) [9].

Challenges in weed Management

Complex Weed Populations in High-Input Farming

Modern agriculture relies on intensified inputs fertilizers, irrigation, and continuous cropping which have altered natural weed patterns and soil health. The decline of traditional methods like crop rotation and organic manuring has allowed weeds to adapt and flourish under new regimes, making management increasingly complex. This demands integrated strategies that blend diverse cultural and chemical controls (Buhler *et al.*, 2000) [14].

Rethinking Economic Thresholds in Weed Control

Economic thresholds are intended to justify weed management only when the cost of intervention is lower than the anticipated crop loss. However, they often neglect the long-term consequences of unchecked weed seed production, such as building persistent soil seed banks, which can lead to more severe weed issues in subsequent seasons. Spatial variation in weed distribution also complicates yield-loss assessment; field heterogeneity means uniform models can overestimate crop damage. To address this, future approaches should develop spatially explicit models for accurate decision-making in precision agriculture (Cardina *et al.*, 1997) [16].

Weed-Crop Competition and Climate Change

Climate change is reshaping the dynamics between crops and weeds. Since most crops are C3 species, they may become more sensitive to competition from C4 weeds under higher temperatures and reduced water availability. Elevated CO₂ levels could temporarily improve crop vigour but may not offset increased parasitic and invasive weed pressure. Research into physiological and molecular responses of crop-weed interactions under climate stress is now a priority (Yamori *et al.*, 2014; Sage

and Kubien, 2007; Rodenburg *et al.*, 2011) [54, 44, 42].

Weed-Pest Interactions and Integrated Management

Weeds often serve as alternative hosts for insect pests and diseases, undermining pest management tactics. Herbicide use and weed presence can modulate the severity of crop diseases and pest infestations. Sublethal herbicide doses may even impact disease expression. Effective management requires that weed and pest dynamics be considered together within integrated pest management strategies (Norris and Kogan, 2000; Duncan and Noling, 1998) [38, 21].

Weeds under Conservation Agriculture

Conservation agriculture practices minimal tillage, permanent soil cover, dynamic rotations improve soil quality and sustainability but can promote the proliferation of certain annual and perennial weeds. Effective weed control under these systems requires cost-efficient integrated strategies, blending post-emergence herbicides with cultural methods. Farmer participation and adaptive management based on local conditions are crucial (Jat *et al.*, 2009; Farooq *et al.*, 2011) [27, 23].

The Spread of Herbicide Resistance

Intensive use and reliance on chemical herbicides have driven the emergence of resistant weed species globally. More than 200 species across multiple crops are now documented as herbicide-resistant. Combatting this trend necessitates rotating herbicide modes of action and integrating non-chemical options. Ongoing research and collaborative programs are vital for developing resistance monitoring and mitigation (Heap, 2010; Busi *et al.*, 2013) [25, 15].

Herbicide-Tolerant Crops and Superweed Evolution

The rise of genetically modified (GM), herbicide-tolerant crops has revolutionized weed control but carries risks overreliance on single herbicides accelerates resistance development, gene flow can enrich wild weed populations, and monocultures can suppress biodiversity. Long-term ecological impacts and the potential emergence of “superweeds” are under critical investigation (Beckie and Warwick, 2010; Owen and Zelaya, 2005) [8, 40].

Persistent Infestations of Parasitic Weeds

Parasitic weeds such as Striga, Orobanch, and Cuscuta cause severe losses, especially in tropical and Mediterranean regions. Despite extensive research, infestations of these root-attaching organisms are increasingly widespread and challenging to control. Biological controls and soil fertility improvements offer partial solutions; however, sustainable regional approaches and innovations are urgently required (EWRS, 2014) [22].

Environmental Concerns with Herbicide Use

Over 95% of applied herbicides may drift beyond target areas, impacting non-target plants, soil, water, and ecosystems. While recommended rates generally avoid major soil biota disruption, long-term and excessive use increases residual risks and ecological imbalance. Monitoring, tighter regulatory standards, and mitigation procedures are essential for safe herbicide application (Miller, 2004; Barman and Varshney, 2008) [34, 5].

Weed Management in Organic Agriculture

Organic farming prohibits synthetic herbicides, relying on mechanical, cultural, and biological methods for weed control.

Although these strategies help, effectiveness and scalability remain challenges. Intercropping, mulching, and bioherbicides are gaining traction but require more research for optimal integration and cost effectiveness (Sumption *et al.*, 2004; Romero *et al.*, 2008; Lundkvist, 2009) ^[46, 43, 33].

Invasion and Impact of Alien Weeds

Invaders such as *Parthenium*, *Lantana*, and *Chromolaena* threaten agricultural systems and biodiversity worldwide. Their competitive growth, lack of natural enemies, and ability to thrive under varied conditions make management difficult. Public awareness, legislative support, and coordinated eradication programs are essential to combat these threats (Yaduraju *et al.*, 2003; Blossey and Notzold, 1995; Abela-Hofbauerová and Münzbergová, 2011) ^[53, 11, 1].

Globalization and Weed Spread

International trade, travel, and relaxed quarantine policies heighten the risk of exotic weeds entering new ecosystems. Lessons from the spread of *Mikania* and *Parthenium* in India underscore the need for rigorous pest risk assessments and improved border controls to prevent new invasions (Biswas, 1934; Holm *et al.*, 1979) ^[10, 26].

Technology Adoption for Improved Weed Management

Despite proven benefits, many Indian farmers have been slow to adopt advanced weed management technologies due to low awareness, limited access to herbicides, and reliance on traditional uses of weeds. Intensive extension education, front line demonstrations, and extension programs and advisory services (including ICT and media) are essential to drive technology uptake and close yield gaps (Bala *et al.*, 2006; Dashora *et al.*, 2011; Wanjala *et al.*, 2003) ^[2, 19, 51].

Precision and Site-Specific Weed Control

Site-specific weed management, enabled by precision agriculture tools, allows targeted herbicide and control applications based on localized weed distribution. This approach promises greater cost efficiency and ecological benefits, but requires robust mapping and technology adoption (Clay *et al.*, 1999; Swinton, 2005) ^[17, 47].

Emerging Opportunities in Weed Science

Since the inception of chemical weed control in the 1940s, weed science has significantly contributed to global food security by enhancing crop yields and reducing labour. However, shifting agronomic contexts such as climate change, evolving cropping systems, and increasing environmental awareness present new avenues for research and innovation in weed management. Integrating weed science with ecology, molecular biology, invasion biology, and ecosystem restoration can foster holistic, efficient, and sustainable weed management approaches.

Development of safer herbicides and application technologies

Research is focusing on creating safer herbicides characterized by low dose requirements and diverse modes of action to replace older, more hazardous chemicals. Advances in herbicide formulations and precision spraying technologies promise to improve application efficiency, reduce chemical use, and mitigate environmental risks.

Enhancement of non-chemical and alternative weed control methods

Growing emphasis on mechanical, cultural, and biological weed

control methods is driving the search for bioactive plant compounds and microbial metabolites as novel herbicidal agents. Such alternative strategies align with environmentally friendly management goals and address increasing concerns over pesticide impacts.

Biotechnology and Genetic Innovations

The application of biotechnology offers opportunities for developing novel herbicide-tolerant crops and tailored biological control agents. These innovations can enhance targeted weed suppression and minimize off-target effects, contributing to integrated weed management (IWM) systems.

Invasive Species Prevention and Management

Climate change may facilitate the spread of invasive alien weed species into new regions, threatening biodiversity and crop productivity. Proactive surveillance, risk assessment, and management strategies are vital to preserving native ecosystems and preventing invasions.

Climate Change Research and Adaptive Weed Management

Understanding how evolving climatic factors influence crop-weed interactions and the performance of herbicides and biocontrol agents is critical. This knowledge will inform adaptive management practices that remain effective under changing environmental conditions.

Nanotechnology Applications

Emerging nanotechnologies hold potential for precision herbicide delivery through nano-composite controlled-release formulations. These formulations may provide sustained, targeted release of active ingredients, reducing repeated applications, environmental residues, and input costs.

Remote Sensing and Precision Agriculture

Utilization of remote sensing tools enables site-specific weed monitoring and management, facilitating reduced herbicide wastage and limiting environmental exposure. Coupled with data analytics, these technologies enhance decision-making for site-targeted interventions.

Advancements in Sustainable Production Systems

Resource-efficient production systems, including conservation agriculture, necessitate specialized weed management knowledge and technologies. Development of new-generation machinery for minimum tillage, sowing, spraying, and residue management supports cost-effective and sustainable weed control.

Information and Communication Technologies (ICT)

ICT and Management Information Systems improve access to weed management knowledge among researchers and farmers, fostering timely knowledge transfer and extension services essential for technology adoption.

Monitoring and Mitigation of Herbicide Residues

Improved diagnostic tools for detecting and quantifying herbicide residues support safer chemical use. Furthermore, innovative decontamination techniques aim to reduce environmental and health hazards associated with herbicide transformation products.

Solar-Powered and Robotic Weed Control

Advances in solar energy-powered devices, such as microwave

weed control systems integrated with sensors, and robotics offer promising environmentally sustainable weed suppression alternatives. These technologies enhance precision and reduce reliance on chemical herbicides.

Utilization of Weed Biomass

Transforming weed biomass into value-added products such as enriched compost, pharmaceuticals, bioremediation agents, and other industrial applications provides economic and ecological incentives for sustainable weed management.

Conclusion

Weeds remain one of the most persistent challenges in agriculture due to their dynamic populations and adaptability. While herbicides have revolutionized weed control, their overuse has led to resistance issues, invasive species spread, and environmental concerns. Integrated Weed Management (IWM), which combines cultural, mechanical, chemical, and biological methods, offers the most sustainable solution. Future strategies must focus on site-specific approaches, innovative technologies, and effective farmer adoption to ensure that crop production remains resilient under increasing food demand, climate change, and land-use pressures.

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