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Management of weeds in the organic production system: A comprehensive review

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Abstract

Weed management in organic production systems presents unique challenges due to the absence of synthetic herbicides and the reliance on natural agricultural practices. Effective weed control is essential for maximizing crop yield while maintaining ecological balance. This review explores various non-chemical strategies employed in organic weed management, with a focus on mechanical, cultural, and biological approaches. Mechanical methods include tillage, mowing, and flaming, whereas cultural practices involve crop rotation, mulching, and cover cropping. Biological control strategies utilize natural enemies, such as insects and allelopathic plants, to suppress weed growth. In addition, integrated approaches that combine multiple methods are discussed to enhance overall weed control efficiency. The review also highlights the importance of soil health and biodiversity in reducing weed pressure. Ultimately, sustainable weed management strategies are critical for preserving the environmental integrity and productivity of organic agricultural systems. This review emphasizes the role of integrated and ecological approaches in effective weed management within organic production systems.

Keywords: Ecological balance, Organic farming, Organic production systems, Soil health, Weed management

Introduction

Organic production systems emphasize natural inputs, soil health, and ecological balance. Fogliatto *et al.* (2023) ^[15] emphasize that weed management in organic agriculture is a “major barrier to yield and adoption” and call for integrated approaches. The challenge is to maintain weed pressure below economic thresholds while preserving the system's ecological integrity. Organic agriculture aims to sustain the health of soils, ecosystems, and people. However, one of its biggest production challenges is weed competition, which can reduce yields by 30-50% in some crops (Pantović *et al.*, 2023) ^[18]. Because synthetic herbicides are prohibited, organic producers rely on an integrated strategy that combines prevention, cultural practices, mechanical control, and ecological balance. In Concept, Principles of Organic Production, organic agriculture is founded on a production philosophy that prioritizes environmental sustainability, soil health, and biodiversity, while avoiding the use of synthetic fertilizers, herbicides, and pesticides. The core principles of organic farming emphasize the utilization of natural ecological processes, preventive management strategies, and diversified cropping systems to sustain long-term productivity and ecosystem stability (Kremen & Miles, 2012 ^[22]; Rodale Institute, 2022) ^[33]. In contrast to conventional systems that often focus on maximizing short-term yields through external inputs, organic production systems aim to enhance system resilience by improving soil biological activity and strengthening crop-environment interactions. The studies of the weed problem in organic farming systems. Weeds are an inherent component of agricultural ecosystems; however, they pose a significant challenge in organic farming due to the absence of chemical weed control options. Under organic management, weeds can establish rapidly and adapt to cultural practices, leading to increased weed pressure and shifts in species composition (Bond & Grundy, 2001; Gallandt, 2014) [9, 16]. Competition from weeds for light, water, nutrients, and space can adversely affect crop establishment and growth. Additionally, dense weed populations may hinder harvesting operations and serve as alternate hosts for pests and diseases (Liebman & Davis, 2000) ^[24]. In some general factors, weeds are a major yield-limiting factor; the role of weed interference is widely recognised as one of the most

significant yield-limiting factors in organic crop production. Yield losses are often most severe during the early stages of crop growth, when crops are less competitive and more susceptible to weed pressure (Chauhan & Opena, 2013) [10]. Studies across various organic cropping systems have demonstrated that ineffective weed management can lead to substantial reductions in yield and increased variability in production outcomes (Bilalis *et al.*, 2010; Tautges *et al.*, 2018) [8, 37]. The persistence of perennial weeds and highly competitive annual species further exacerbates yield losses, particularly under reduced tillage and non-chemical management regimes (Travlos *et al.*, 2017) [39]. In addition to direct impacts on yield, weed pressure significantly increases labor requirements and production costs, thereby affecting the economic viability of organic farming systems (Lichtenberg & Swinton, 2009) [25]. It shows the need for integrated weed management in organic agriculture, given the limitations of single-method weed control approaches; organic farming systems increasingly rely on integrated weed management (IWM) strategies. Integrated weed management involves the combined application of cultural, mechanical, biological, and preventive practices to suppress weed populations and reduce their competitive advantage over crops (Melander *et al.*, 2005; Baliyar & Dahiya, 2024) [4, 26]. Practices such as crop rotation, cover cropping, mulching, mechanical weeding, and conservation-oriented soil management form the foundation of IWM and align closely with the ecological principles of organic agriculture (Baral, 2013; Dash *et al.*, 2020) [5, 11]. Recent advancements, including precision weed management and landscape-level agroecological approaches, have further enhanced the potential of IWM to improve weed control efficiency while maintaining environmental sustainability (Agronomy for Sustainable Development, 2024; Monteiro & Santos, 2022) [3, 29]. Despite ongoing advancements, weed management remains a key constraint to yield stability and profitability in organic farming systems, with outcomes often varying across crops, regions, and production environments (DeDecker *et al.*, 2017; Kushal *et al.*, 2024) [12, 23]. In this context, the objective of the present review is to critically synthesize existing knowledge on weed management in organic agriculture. Specifically, this review aims to examine weed dynamics in organic farming systems; analyze the factors influencing weed infestation; and evaluate the principles of weed management in organic production systems. It further explores various weed management approaches adopted in organic farming, assesses weed management practices in major organic crops, and analyzes the key challenges associated with organic weed control. In addition, the review highlights recent advances and innovations in organic weed management and identifies future research needs and policy implications, particularly in relation to bioherbicide-based and integrated weed management strategies.

Weed Dynamics in Organic Farming

Weed Flora in Organic Fields

Organic cropping systems are particularly susceptible to weed infestation due to the absence of synthetic herbicides. Weed flora in organic fields is highly diverse and is influenced by crop type, soil management practices, climate, and cropping history (Ameena *et al.*, 2025; Bhadu & Kaswan, 2022) [1, 7]. These systems often harbor a mixture of annual, biennial, and perennial weed species, each exhibiting distinct growth habits and competitive abilities. The diversity of weeds in organic fields can pose significant challenges to crop production; however, in some cases, it may also contribute to ecological balance by

supporting beneficial insects and enhancing soil microbial activity (Gallandt, 2014) [16].

Common Weeds in Organic Systems

Certain weed species consistently dominate organic fields due to their adaptability to low-input environments. In cereal crops, species such as *Chenopodium album*, *Amaranthus spp.*, and *Echinochloa crus-galli* are commonly prevalent, whereas broadleaf crops often face competition from *Portulaca oleracea* and *Convolvulus arvensis* (Baral, 2013; Singh *et al.*, 2020) [5, 34]. Perennial species such as *Cirsium arvense* and *Poa annua* pose long-term management challenges due to their extensive root systems and their ability to regenerate from vegetative fragments (Travlos *et al.*, 2017) [39]. Understanding the composition and dynamics of weed flora is critical for designing effective Integrated Weed Management (IWM) strategies.

Shifts in Weed Flora under Organic Management

Long-term organic practices often lead to shifts in weed populations. The reduction in chemical inputs favors slow-growing and competitive species that can coexist with crops under mechanical and cultural management practices (Bilalis *et al.*, 2010; Bond & Grundy, 2001) [8, 9]. Crop rotation, cover cropping, and soil disturbance patterns play a significant role in influencing these shifts, often reducing the dominance of aggressive annual weeds while increasing the diversity of perennial and low-growing species (Dash *et al.*, 2020; Monteiro & Santos, 2022) [11, 29]. Monitoring these changes is essential for predicting emerging weed threats and adapting management strategies accordingly.

Factors influencing weed infestation in organic farming

Weed infestation in organic farming systems is governed by multiple interacting factors, including the soil seed bank, cropping history, tillage and residue management, and climatic and ecological conditions. Each of these factors plays a distinct yet interconnected role in shaping weed population dynamics, species composition, and the overall effectiveness of weed management strategies. The soil seed bank serves as the primary source of weed emergence and determines the potential intensity and diversity of weed infestations. In organic systems, the absence of synthetic herbicides allows a broader range of weed species to survive and replenish the seed bank, thereby increasing long-term management complexity (Ameena *et al.*, 2025; Mishra, 2025; Bond & Grundy, 2001) [9, 27]. In contrast, cropping history influences weed populations indirectly by altering ecological niches. Diverse crop rotations and intercropping systems disrupt weed life cycles and reduce species dominance, whereas continuous monocropping promotes the proliferation of specific, highly competitive weeds (Liebman & Davis, 2000; Bilalis *et al.*, 2010) [8, 24]. Similarly, tillage and residue management directly affect weed seed distribution and germination conditions. While tillage manipulates the vertical placement of weed seeds in the soil profile, crop residues act as a physical and ecological barrier that suppresses weed emergence by modifying light, temperature, and moisture conditions (Baral, 2013; Melander *et al.*, 2005; Dash *et al.*, 2020; Monteiro & Santos, 2022) [5, 11, 26, 29]. On the other hand, climatic and ecological conditions determine the adaptability and competitiveness of weed species. Environmental variables such as temperature, rainfall, and soil properties influence weed germination, growth, and spatial distribution, making weed management highly site-specific (Ameena *et al.*, 2025; Gallandt, 2014) [1, 16]. In comparison, the soil seed bank and climatic

factors act as foundational drivers of weed dynamics, while cropping history and tillage practices function as management-driven modifiers. An integrated understanding of these factors is therefore essential for developing effective and locationspecific integrated weed management (IWM) strategies in organic agriculture. The below given table 1, shows the Comparative Analysis of Key Factors Influencing Weed Infestation in Organic Farming.

Table 1: Comparative Analysis of Key Factors Influencing Weed Infestation in Organic Farming

Factor	Key Role in Weed Dynamics	Mechanism of Influence	Impact on Weed Management	Research Implication
Soil Seed Bank	Primary source of weed emergence	Stores viable seeds; influenced by dormancy and species diversity	Increases long-term weed pressure and diversity	Requires preventive and long-term management strategies
Cropping History	Alters weed species composition	Crop rotation and diversity disrupt weed life cycles	Reduces dominance of specific weeds	Supports ecological weed suppression strategies
Tillage & Residue Management	Controls weed seed placement and germination conditions	Tillage affects seed depth; residues act as mulch limiting light and moisture changes	Can suppress or stimulate weed emergence	Critical for mechanical and cultural control planning
Climate & Ecological Conditions	Determines weed adaptability and distribution	Temperature, rainfall, soil properties affect growth and competition	Leads to region-specific weed problems	Necessitates site-specific IWM approaches

Principles of weed management in organic production systems

Weed management in organic farming is guided by a set of ecological principles that emphasize sustainability, system resilience, and long-term regulation rather than immediate eradication. The four major principles—prevention, crop-weed competition balance, biodiversity-based suppression, and integrated weed management (IWM)—operate at different stages and scales but are highly complementary in their effects.

Prevention rather than eradication

Prevention rather than eradication serves as the foundational strategy in organic systems. In the absence of synthetic herbicides, emphasis is placed on minimizing weed establishment and reducing the addition of viable seeds to the soil seed bank. Practices such as the use of clean seed material, proper composting of organic manures, sanitation of farm equipment, timely field preparation, crop rotation, and cover cropping collectively restrict weed introduction and proliferation (Bond & Grundy, 2001; Gallandt, 2014) [9, 16]. This approach is proactive and longterm in nature, focusing on reducing future weed pressure rather than controlling existing infestations.

Crop-weed competition balance

In contrast, the crop-weed competition balance principle focuses on enhancing crop competitiveness during critical growth stages. Instead of aiming for complete weed elimination, this approach seeks to maintain weed populations below economically damaging thresholds. Agronomic practices such as optimal sowing time, increased seed rates, narrow row spacing, and the use of competitive cultivars improve crop vigor and suppress weed growth (Mohler & DiTommaso, 2010; Melander *et al.*,

2005) [26, 28]. This principle is particularly important during the early stages of crop development, when weed competition has the greatest impact on yield.

Biodiversity-based weed suppression

The biodiversity-based weed suppression principle operates at the ecosystem level. It relies on increasing plant diversity through crop rotations, intercropping, and cover crops to reduce resource availability for weeds and disrupt their ecological niches. Additionally, organic mulches and cover crops suppress weeds through shading, physical barriers, and allelopathic effects, while enhanced biodiversity promotes soil microbial activity and natural seed predation (Kremen & Miles, 2012; Bilalis *et al.*, 2010) [8, 22]. This approach not only reduces weed pressure but also enhances overall agroecosystem resilience.

Integrated Weed Management

The Integrated Weed Management (IWM) represents a holistic and adaptive strategy that combines all available methods—cultural, mechanical, biological, and ecological—to achieve sustainable weed control. Unlike individual approaches, IWM integrates preventive, competitive, and suppressive strategies to provide consistent and effective weed management under diverse conditions (Liebman & Davis, 2000; Rodale Institute, 2022) [24, 33]. Recent innovations, such as precision weed management and anaerobic soil disinfestation, have further strengthened the effectiveness of IWM in organic systems (Monteiro & Santos, 2022; Singh & Sharma, 2024) [29, 35]. From a comparative perspective, prevention acts as a proactive foundation, crop-weed competition as a short-term yield protection mechanism, biodiversity as an ecological regulator, and IWM as an integrative framework that combines all strategies. Together, these principles form a comprehensive and sustainable approach to weed management in organic agriculture. The Comparative analysis of organic weed management principles was shown in the Table 2.

Table 2: Comparative Analysis of Organic Weed Management Principles

Principle	Core Objective	Key Mechanisms	Time Scale	Role in Organic Systems
Prevention rather than eradication	Reduce weed introduction and seed bank buildup	Clean seeds, sanitation, crop rotation, cover cropping	Long-term	Foundation for sustainable weed management
Crop-weed competition balance	Enhance crop competitiveness	Optimal sowing, seed rate, spacing, competitive cultivars	Short-term	Minimizes yield loss during critical growth stages
Biodiversity-based suppression	Regulate weeds through ecological diversity	Crop diversity, intercropping, mulching, allelopathy, microbial activity	Medium to long	Improves resilience and natural weed suppression
Integrated Weed Management (IWM)	Achieves sustainable weed control	Combination of cultural, mechanical, biological, and ecological methods	Continuous	Holistic and adaptive strategy for effective weed management

Weed Management Approaches in Organic Production Systems

Weed management in organic agriculture is guided by ecological principles and long-term sustainability rather than short-term eradication. As synthetic herbicides are not permitted, organic systems rely on a combination of preventive, cultural,

mechanical, physical, and biological approaches that collectively regulate weed populations. The effectiveness of organic weed management depends on a thorough understanding of weed ecology and the integration of multiple practices within an Integrated Weed Management (IWM) framework.

Preventive Weed Management

Preventive weed management is the most fundamental and cost-effective approach in organic farming. Pantovic *et al.* (2023) [18] its primary objective is to avoid the introduction, establishment, and reproduction of weeds, thereby reducing weed pressure over time. This approach focuses on minimizing additions to the soil weed seed bank, which serves as the principal source of future infestations. Key preventive measures include the use of clean and certified seeds, welldecomposed compost, and weed-free irrigation water. Farm sanitation is critical, as weeds can spread through contaminated machinery, tools, and planting materials. Additionally, timely field preparation and proper water and nutrient management favor crop growth over weeds. Crop rotation and cover cropping further strengthen prevention by disrupting weed life cycles and limiting the dominance of specific weed species. In organic systems, prevention is considered a long-term investment that reduces reliance on intensive control measures in subsequent seasons.

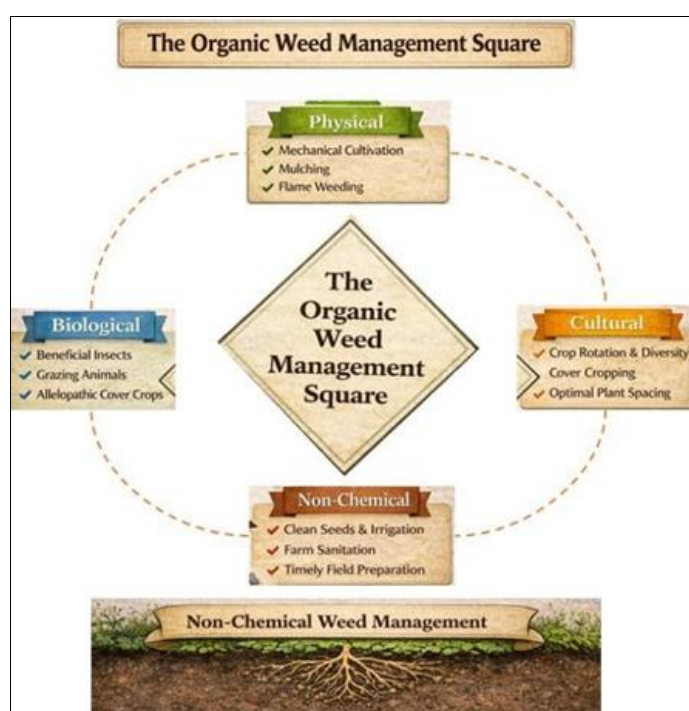


Fig 1: Square of organic weed management (Firat Pala, 2021)

Cultural Weed Management

Cultural weed management aims to enhance crop competitiveness, enabling crops to suppress weeds naturally. This approach is based on the principle that healthy and well-managed crops serve as the most effective means of weed control. By modifying agronomic practices, farmers can create conditions that favor crop growth over weed development. Key practices include optimizing sowing time, maintaining appropriate plant spacing, increasing seed rates, and selecting competitive crop cultivars. Early and uniform crop establishment allows efficient utilization of light, nutrients, and moisture, thereby limiting resources available to weeds. Crop rotation plays a central role by preventing weed adaptation to a single cropping system. Additionally, cover crops and green

manures suppress weeds through shading, competition, and allelopathic effects. Cultural weed management is particularly advantageous as it integrates seamlessly with routine crop production practices, making it both practical and sustainable (Ameena *et al.*, 2025) [1].

Mechanical and Physical Weed Management

Mechanical and physical methods are among the most widely used weed control strategies in organic farming. These methods involve the direct removal or destruction of weeds through physical force or soil disturbance. They are especially critical during the early stages of crop growth when weed competition is most intense. Common practices include hand weeding, hoeing, inter-row cultivation, harrowing, and mowing. Technological advancements, such as precision weeders, tine weeders, and flame weeders, have improved the efficiency and precision of mechanical control while minimizing crop damage. Physical methods, including mulching with crop residues, straw, or biodegradable films, suppress weed emergence by blocking light and modifying soil temperature and moisture conditions. Fogliatto *et al.* (2023) [15], these methods require precise timing, skilled operation, and often involve higher labor inputs. Excessive soil disturbance may also negatively affect soil structure and microbial activity, emphasizing the need for their balanced application.

Biological Weed Management

Biological weed management utilizes living organisms and natural biological processes to suppress weed populations. Although less commonly applied as a standalone approach, it plays a supportive role in organic systems. Biological control strategies include the use of insects, pathogens, grazing animals, and competitive plant species to reduce weed growth and reproduction. Cover crops and living mulches are widely adopted biological tools that suppress weeds through competition and allelopathy. Soil microorganisms contribute to the natural decay of weed seeds, thereby reducing seed viability in the soil seed bank. In certain systems, controlled grazing by livestock is used to manage weeds in perennial crops and pastures. (Kushal *et al.*, 2024) [23], Biological methods alone may not provide complete control, they enhance system resilience and contribute to long-term weed regulation when integrated with other approaches.

Integrated Weed Management (IWM)

Integrated Weed Management (IWM) represents the most effective and sustainable strategy for weed control in organic farming systems. It involves the strategic integration of preventive, cultural, mechanical, physical, and biological methods based on local environmental conditions, cropping systems, and weed ecology. Rather than relying on a single method, IWM emphasizes adaptability, ecological balance, and system-based management. Within this framework, preventive measures reduce initial weed pressure, cultural practices enhance crop competitiveness, mechanical and physical methods provide timely weed control, and biological processes support long-term suppression. The success of IWM depends on a comprehensive understanding of weed biology, continuous monitoring of weed populations, and the timely application of appropriate control measures. By integrating multiple approaches, IWM enables effective weed management while maintaining soil health, biodiversity, and economic viability in organic production systems Agronomy for Sustainable Development (2024) [3].

Table 3: Summary of Major Weed Management Strategies in Organic Farming

Strategy Type	Examples / Methods	Advantages	Limitations	Key References
Preventive	Crop rotation, sanitation, clean seed	Reduces weed seedbank; sustainable long-term	Requires long planning cycles	Pantovic <i>et al.</i> (2023)
Cultural	Competitive cultivars, dense sowing	Enhances crop competitiveness	Crop-specific, limited flexibility	Ameena <i>et al.</i> (2025)
Mechanical/Physical	Tillage, flame weeding, mulching	Immediate suppression, chemical-free	Labor-intensive; soil disturbance issues	Fogliatto <i>et al.</i> (2023)
Biological/Ecological	Allelopathy, intercropping, predators	Promotes biodiversity, sustainable suppression	Slow establishment, variable efficacy	Kushal <i>et al.</i> (2024)
Landscape-Level	Habitat management, crop mosaics	Long-term weed population regulation	Requires coordination among farms	Agronomy for Sustainable Development (2024)

Organic Weed Management in Major Organic Crops

Weed management remains one of the most critical challenges in organic crop production, particularly in major food and fiber crops where yield stability is essential. In the absence of synthetic herbicides, organic weed management relies on ecological understanding, cropspecific strategies, and integrated approaches. Although weed control practices vary depending on crop characteristics such as growth habit, planting geometry, crop duration, and competitiveness, the underlying principles—prevention, cultural manipulation, mechanical intervention, biological regulation, and integration—remain consistent (Bond & Grundy, 2001; Gallandt, 2014) ^[9, 16].

Organic Weed Management in Cereals (Rice, Wheat, Maize)

Cereal crops form the backbone of organic farming systems but are highly vulnerable to earlyseason weed competition. In organic rice systems, weeds such as *Echinochloa spp.*, *Cyperus spp.*, and various broadleaf species can cause significant yield losses if not effectively managed. Cultural practices such as stale seedbed preparation, timely transplanting or direct seeding, higher seed rates, and appropriate water management play a central role in weed suppression (Chauhan & Opena, 2013; Singh *et al.*, 2020) ^[10, 34]. Mechanical weed control methods, including hand weeding and the use of rotary weeders, are widely practiced during critical growth stages (Singh *et al.*, 2020; Mishra, 2025) ^[27]. Additionally, crop rotation with legumes and the inclusion of cover crops help reduce weed pressure by disrupting weed life cycles and improving soil fertility (Liebman & Davis, 2000; Dash *et al.*, 2020) ^[11, 24]. In organic wheat and maize systems, strategies such as narrow row spacing, the use of competitive cultivars, intercropping, and timely mechanical weeding are commonly adopted. Studies indicate that early mechanical intervention combined with enhanced crop competitiveness is essential for effective weed control in cereal-based organic systems (DeDecker *et al.*, 2017; Tautges *et al.*, 2018) ^[12, 37].

Organic Weed Management in Pulses and Oilseeds

Pulses and oilseeds are particularly susceptible to weed competition during early growth stages due to their slow initial development. In organic systems, cultural practices such as optimal sowing time, increased seed rates, and diversified crop rotation are crucial for improving crop competitiveness (Raj *et al.*, 2023; Balihar & Dahiya, 2024) ^[4, 32]. Cover cropping and residue mulching are effective strategies for suppressing annual weeds in crops such as soybean, mustard, and groundnut. These practices not only reduce weed emergence but also conserve soil moisture and improve soil structure (Bilalis *et al.*, 2010; Barros & Basch, 2014) ^[6, 8]. Mechanical methods, including inter-row cultivation and hand weeding, remain essential, particularly in widely spaced crops. Organic oilseed systems also benefit from

biodiversitybased approaches, where crop diversification and intercropping reduce the dominance of problematic weed species (Kremen & Miles, 2012; Ameena *et al.*, 2025) ^[1, 22].

Organic Weed Management in Vegetables

Vegetable crops are among the most weed-sensitive in organic systems due to their wide spacing, high nutrient demand, and slow canopy development. Effective weed management in organic vegetables requires intensive and timely intervention using multiple strategies (eOrganic, 2016) ^[14]. Mulching with organic materials, biodegradable films, or crop residues is one of the most effective weed control methods, as it suppresses weed emergence by blocking light and modifying soil microclimate while improving soil organic matter (Baral, 2013; Bhadu & Kaswan, 2022) ^[5, 7]. Mechanical approaches such as hand weeding, flame weeding, and precision cultivation tools are widely used, particularly in high-value crops (Melander *et al.*, 2005; Monteiro & Santos, 2022) ^[26, 29]. Biological methods, including cover crops, living mulches, and enhanced soil microbial activity, contribute to long-term weed suppression by reducing weed seed viability and emergence (Gallandt, 2014; Fogliatto *et al.*, 2023) ^[15, 16].

Organic Weed Management in Fiber Crops (Cotton)

Organic cotton production faces significant challenges from both annual and perennial weeds. Research indicates that integrating tillage practices with cover cropping and organic nutrient management can significantly reduce weed density while maintaining crop yield (Bilalis *et al.*, 2010) ^[8]. Mechanical cultivation, hand hoeing, and residue retention are key weed control practices in organic cotton systems. Additionally, crop rotation and cover cropping improve soil health and disrupt weed life cycles, thereby contributing to sustainable weed suppression (Travlos *et al.*, 2017; Golijan Pantović *et al.*, 2023) ^[18, 39].

Organic Weed Management in Perennial Crops and Orchards

In perennial cropping systems such as orchards and plantations, weed management focuses on minimizing competition while maintaining protective soil cover. Practices such as mulching, cover cropping, and controlled grazing are widely used to suppress weeds and prevent soil erosion (Travlos *et al.*, 2017) ^[39]. Mechanical mowing and strip cultivation are commonly adopted, while biological processes, including enhanced soil microbial activity and weed seed predation, contribute to long-term weed regulation (Gallandt, 2014; Fogliatto *et al.*, 2023) ^[15, 16].

Integrated Weed Management across Organic Crops

Across all major organic crops, Integrated Weed Management

(IWM) is recognized as the most effective and sustainable approach. IWM integrates preventive, cultural, mechanical, physical, and biological practices based on crop type, weed flora, and local agroecological conditions (Liebman & Davis, 2000; Rodale Institute, 2022) [24, 33]. Although organic weed management may involve higher labor and management costs, economic analyses indicate that integrated approaches improve long-term profitability by reducing weed pressure and enhancing system resilience (Lichtenberg & Swinton, 2009) [25]. Furthermore, emerging technologies such as precision weed management and anaerobic soil disinfestation are expanding the scope and efficiency of IWM in organic agriculture (Monteiro & Santos, 2022; Singh & Sharma, 2024) [29, 35].

Challenges in organic weed management systems

Despite its ecological benefits, organic weed management remains one of the most challenging aspects of organic crop production. The absence of synthetic herbicides necessitates reliance on labor-intensive and management-intensive practices. Although organic weed control can be effective, several constraints limit its efficiency and widespread adoption, particularly in largescale and resource-limited farming systems. The Fig. 2. explains about different challenges and solutions in organic weed management system.



Fig 2: Challenges and solutions in organic weed management system.

High Labour Requirement

One of the most significant challenges in organic weed management is the high demand for manual and mechanical labor. Practices such as hand weeding, hoeing, inter-row cultivation, and mulching require substantial human effort, particularly during the early stages of crop growth when weed competition is most critical. In high-value crops such as vegetables, repeated manual weeding is often unavoidable, leading to increased production costs. Furthermore, labor availability is becoming increasingly uncertain due to rural-to-

urban migration and rising wage rates. Consequently, smallholder farmers may struggle to manage weeds effectively, while large-scale organic farms face challenges in maintaining economic viability under high labor costs.

Narrow Timeline of Operations

Organic weed management is highly time-sensitive, and even minor delays can result in significant yield losses. Most mechanical and cultural weed control measures must be implemented within a narrow time window, particularly during the early crop growth stages. Failure to control weeds during this critical period allows them to outcompete crops for essential resources such as light, nutrients, and moisture, leading to irreversible yield reductions. Additionally, unpredictable weather conditions further complicate timely operations. Rainfall can delay field activities, while prolonged wet or dry periods may accelerate weed emergence. Unlike conventional systems, organic farmers have limited corrective options once weeds escape early control, making precise timing essential yet difficult to achieve.

Limited Effectiveness of Single Weed Control Methods

No single weed management method is fully effective under organic production systems. Mechanical, cultural, physical, or biological approaches, when used individually, often provide only partial control. For instance, mechanical weeding may effectively remove emerged weeds but can also stimulate the germination of buried weed seeds due to soil disturbance. Similarly, mulching may suppress annual weeds but is less effective against perennial species. This limitation necessitates the integration of multiple strategies, increasing management complexity and requiring a high level of technical knowledge. Farmers must continuously adapt their practices based on weed flora, crop type, and environmental conditions, making organic weed management more demanding than conventional approaches.

Persistence of the Weed Seed Bank

The persistence of weed seeds in the soil seed bank represents a major biological challenge in organic farming systems. Many weed species produce large quantities of seeds that can remain viable for several years or even decades. In the absence of chemical control, preventing seed production entirely is difficult, particularly under high weed pressure. Moreover, soil disturbance associated with mechanical weeding can bring dormant seeds to the surface, triggering new weed emergence. Consequently, farmers often encounter recurring weed problems despite consistent management efforts. Effective reduction of the weed seed bank requires sustained preventive strategies over multiple cropping cycles, demanding long-term commitment and strategic planning.

Economic Constraints

Economic limitations significantly influence the feasibility of organic weed management. The combined costs of labor, machinery, mulching materials, and repeated field operations can be substantial. For small and marginal farmers, these costs may outweigh the economic benefits associated with organic certification and premium market prices, particularly during the transition period. Additionally, yield losses due to inadequate weed control may be higher in organic systems if management practices are not optimally implemented. Limited access to specialized equipment and technical support further constrains effective weed management, especially in developing regions.

These economic challenges highlight the need for cost-effective, scalable, and locally adaptable weed management solutions.

Recent advances and innovations in organic weed management

Organic weed management has traditionally depended on labor-intensive operations and simple mechanical tools. However, recent technological and knowledge-based innovations are reshaping this landscape. These advancements aim to improve precision, reduce labor requirements and soil disturbance, and integrate real-time decision-making, thereby making organic systems more productive and sustainable.

Precision Mechanical Weeders

Precision mechanical weeders have evolved from simple inter-row cultivators into sensor-aided, automated systems capable of distinguishing between weeds and crops. Modern weeders incorporate GPS guidance, real-time sensing, and machine vision, enabling centimeter-level accuracy in weed removal while minimizing crop injury and soil disturbance. These tools retain the ecological benefits of mechanical weeding while adding digital precision and automation, thereby significantly addressing labor constraints in organic systems. Recent research highlights that the integration of artificial intelligence (AI), machine vision, and robotics into mechanical weeders enhances weed detection and removal under varying field conditions, reducing dependence on manual labor and improving sustainability. These systems can now differentiate weeds from crops using RGB imaging, LiDAR, and deep learning-based detection algorithms, enabling targeted, non-chemical weed removal.

Advanced Mulch-Based Weed Suppression Systems

Mulch remains a core component of organic weed management; however, recent innovations have enhanced its effectiveness and multifunctionality. In addition to traditional crop residues, biodegradable mulches and living mulches provide effective weed suppression by blocking light, moderating soil temperature, and conserving moisture. Modern mulch systems are designed to complement cover cropping and reduced tillage practices, thereby enhancing soil health and biodiversity while suppressing weed emergence. Emerging approaches also integrate mulch systems with precision tools, allowing farmers to combine ground cover with targeted mechanical interventions, ultimately reducing overall weed pressure while supporting ecological functions.

Robotic Weed Control Technologies

Robotic technologies represent a transformative frontier in organic weed management. Powered by machine learning, deep learning, and advanced sensors, autonomous and semiautonomous robots can scout fields, distinguish weeds from crops, and perform precise weeding operations. For example, robotic platforms such as the open-source Agri Cruiser demonstrate that affordable and customizable systems can navigate crop rows and effectively reduce weed populations while minimizing crop damage. This significantly reduces labor requirements and improves operational efficiency. Experimental studies have also explored directed-energy weed control robots that use machine learning for weed identification and apply non-chemical energy sources to eliminate weeds without soil disturbance. These systems have demonstrated high classification accuracy in initial field trials. With ongoing advancements in real-time sensing, autonomous navigation, and

adaptive control, robotic weeders are becoming increasingly capable of operating across diverse crops and field conditions.

Atomization and Thermal/Targeted Weed Control Techniques

Atomization and targeted thermal methods are emerging as promising non-chemical weed control alternatives. These systems deliver heat, steam, or finely atomized natural agents directly to weeds at specific growth stages, causing thermal injury without the use of herbicides. Although still in the early stages of adoption, these technologies show strong potential for controlling young weed seedlings efficiently and reducing subsequent weed pressure in organic systems. Additionally, laser- and directed-energy-based weeders are gaining attention as precise, non-disruptive tools. Ongoing research demonstrates high accuracy and efficiency in plant detection and targeted weed removal using deep learning frameworks.

Knowledge Innovation and Decision-Support Systems

Beyond hardware innovations, knowledge-based advancements and digital decision-support systems are playing a crucial role in transforming organic weed management. Researchers and extension services are developing image databases, predictive models, and farmer-friendly tools capable of forecasting weed emergence patterns, recommending optimal interventions, and integrating multiple control strategies within an Integrated Weed Management (IWM) framework. AI-powered crop-weed discrimination models, including transformer-based and deep learning segmentation systems, are significantly improving real-time weed detection accuracy. These advancements enable more efficient use of precision technologies such as robotic weeders and targeted thermal systems. This transition toward data-driven weed management allows farmers to optimize the timing of operations, reduce unnecessary interventions, and make proactive decisions that enhance ecological stability and farm profitability.

Future Research Needs and Policy Implications in Bioherbicide-Based and Integrated Weed Management

Weed management is a critical component of sustainable agriculture, significantly influencing crop productivity and ecological balance. Although conventional herbicides are effective, their continued use has led to concerns such as herbicide resistance, soil degradation, and environmental pollution (Ameena *et al.*, 2025; Anmolpreet *et al.*, 2024) ^[1, 2]. Bioherbicides, derived from natural products or microbial agents, represent a promising eco-friendly alternative. The integration of bioherbicides with crop-specific and region-specific weed management strategies can enhance agricultural sustainability while reducing dependence on synthetic chemicals (Baliyar & Dahiya, 2024; Mishra, 2025) ^[4, 27].

Efficiency of Bioherbicides

The effectiveness of bioherbicides depends on their target specificity, formulation, and environmental stability. However, several research gaps remain:

- **Research Needs:** Target specificity: Bioherbicides require detailed evaluation against dominant weed species while ensuring crop safety (Bhadu & Kaswan, 2022; Chauhan & Opena, 2013) ^[7, 10]. Formulation and field stability: Microbial and allelopathic bioherbicides must maintain efficacy under diverse climatic and soil conditions (Mishra, 2025) ^[27]. Integration with other methods: Combining bioherbicides with cultural, mechanical, or other approaches

can enhance weed control within Integrated Weed Management (IWM) systems (Dash *et al.*, 2020; Golijan Pantović *et al.*, 2023) ^[11, 18]. Environmental impact: Limited research exists on long-term effects on soil microbiomes, non-target organisms, and ecosystem health (Mohler & DiTommaso, 2010) ^[28].

- **Policy Implications:** Development of regulatory frameworks for bioherbicide approval, including fast-track mechanisms and quality standards. Promotion of eco-friendly technologies through subsidies and incentives. Integration of bioherbicide guidelines into national crop protection policies (Rodale Institute, 2022; Lichtenberg & Swinton, 2009) ^[25, 33].

Crop-Specific Weed Management

Crop-specific weed management focuses on addressing unique weed-crop interactions to optimize control strategies for individual cropping systems.

- **Research Needs:** Identification of dominant weed complexes for specific crops (Raj *et al.*, 2023; Singh *et al.*, 2020) ^[32, 34]. Development of tailored bioherbicide formulations and cultural practices to reduce weed competition (Baral, 2013; Bilalis *et al.*, 2010) ^[5, 8]. Economic evaluation of crop-specific interventions to support adoption among resource-limited farmers (Lichtenberg & Swinton, 2009) ^[25].
- **Policy Implications:** Integration of crop-specific IWM strategies into precision agriculture programs (Monteiro & Santos, 2022) ^[29]. Increased funding for research and development of cropspecific bioherbicides and management practices (Kushal *et al.*, 2024) ^[23]. Standardization of cropspecific weed management guidelines within national agricultural policies (Ameena *et al.*, 2025) ^[1].

Region-Specific Weed Dynamics

Weed populations, growth patterns, and competitiveness vary across agro-climatic regions, necessitating localized management approaches.

- **Research Needs:** Regional mapping of dominant weed species and ecological studies on weed-crop interactions (Agronomy for Sustainable Development, 2024; Fogliatto *et al.*, 2023) ^[3, 15]. Assessment of climate change impacts on weed dynamics across regions (DeDecker *et al.*, 2017) ^[12]. Development of region-specific bioherbicide formulations and IWM strategies (Barros & Basch, 2014; Melander *et al.*, 2005) ^[6, 26].
- **Policy Implications:** Formulation of region-specific weed management strategies to improve sustainability and efficiency (Bond & Grundy, 2001) ^[9]. Strengthening of local research institutions and extension systems for continuous monitoring and advisory support (Gallandt, 2014) ^[16]. Promotion of public-private partnerships to develop regionally adapted bioherbicides (Kremen & Miles, 2012) ^[22].

Extension Strategies and Capacity Building

Effective knowledge transfer and capacity building are essential for the adoption of bioherbicides and integrated weed management practices.

- **Research Needs:** Evaluation of training programs, digital tools, and participatory approaches in promoting adoption (eOrganic, 2016; Tautges *et al.*, 2018) ^[14, 37]. Development of farmer-friendly communication tools to simplify complex weed management strategies (Bhadu & Kaswan, 2022;

Mishra, 2025) ^[7, 27].

- **Policy Implications:** Investment in training programs for extension personnel and farmers on bioherbicide application and IWM practices (Rodale Institute, 2022; Singh & Sharma, 2024) ^[33, 35]. Promotion of digital advisory platforms for real-time weed management decision-making (Monteiro & Santos, 2022) ^[29]. Encouragement of on-farm demonstrations and participatory research to adapt technologies to local conditions (Travlos *et al.*, 2017; Dash *et al.*, 2020) ^[11, 39].

Conclusions

Organic weed management is a critical component of sustainable agriculture, directly influencing crop productivity, soil health, and ecological balance. In contrast to conventional systems, organic farming relies on ecological principles and integrated approaches rather than synthetic herbicides. This review highlights that weed dynamics in organic systems are complex and influenced by factors such as soil seed banks, cropping history, and environmental conditions, requiring a thorough understanding of weed ecology. Preventive, cultural, mechanical, physical, and biological methods form the foundation of organic weed management, with Integrated Weed Management (IWM) emerging as the most effective strategy across diverse cropping systems. However, challenges such as high labor requirements, narrow operational windows, persistent weed seed banks, and economic constraints continue to limit its efficiency and large-scale adoption. Recent advancements in precision weeding technologies, robotics, mulch systems, and decision-support tools offer promising solutions to enhance efficiency and reduce labor dependency. Additionally, the integration of bioherbicides and region- and crop-specific strategies presents new opportunities for sustainable weed control. Overall, a holistic, knowledge-driven, and innovation-supported approach is essential to improve the productivity, resilience, and sustainability of organic weed management systems.

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