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A review on challenges and emerging opportunities for weed management in organic agriculture

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Abstract
Weed control is the most difficult and enduring challenge in organic crop production systems. Managing weeds below economic thresholds is critical since most growers face significant yield penalty during the initial years of organic transition. There is renewed interest in using integrated weed management strategies that involve cultural, mechanical, biological and biochemical approaches to support crop production and enhance ecosystem services. Here, we discuss current weed management issues faced by organic growers such as soil and water conservation, farming systems and farm characteristics, farmers perception of weeds, climate change impact and species shift and technology availability and cost. Emerging opportunities such as cultural (stale seedbed, agronomic configurations, mulching, crop rotation and conservation tillage), mechanical (hoeing, soil solarization, hot water treatment, flame weeding and electrocution), biochemical (organically derived herbicides, fatty acids and allelopathic effect), biological (insect herbivores, plant pathogens, and microbial bioherbicides) and other novel technologies (precision farming, lasers and robotics) is also discussed, which may improve weed management while maximizing ecosystem services Dhakal *et al*. (2024) [13].

Keywords: Organic agriculture, challenges and emerging opportunities, ecosystem services

Introduction
Organic agriculture originated from the intentional efforts of individuals aiming to establish an optimal relationship between the earth and humanity. Over time, the field of organic agriculture has grown more complex, facing significant challenges such as entering the policymaking arena, accessing global markets, and transforming organic products into commodities Dhakal *et al*. (2024) [13]. The past two decades have seen a heightened global awareness of environmental preservation and food quality. Enthusiastic supporters of organic farming believe it can address these issues and contribute to the holistic development of rural areas. After nearly a century of evolution, organic agriculture is now gaining mainstream acceptance and holds significant potential commercially, socially, and environmentally. While it continues to build on the foundational principles of healthy soil, food, and people, modern organic agriculture now places environmental sustainability at its core. In India, organic farming is not a new concept; traditionally, farming was exclusively organic, utilizing natural pesticides and organic manures derived from plants and animals. However, during the 1950s and 1960s, India's growing population led to food scarcity, prompting the government to import food grains and push for increased domestic food production for greater food security. The Green Revolution, spearheaded by Dr. M. S. Swaminathan, introduced high-yielding varieties, chemical fertilizers, synthetic pesticides, mechanization, and irrigation projects, which successfully resolved the food crisis and achieved self-sufficiency. However, over time, these practices resulted in issues such as stagnant or declining crop productivity, reduced soil fertility, salinity, lower water tables, and environmental pollution. Farmers have since recognized that organic farming offers the best solution to these challenges. Organic agriculture is a system that maintains the health of soil, ecosystems, and people by relying on ecological processes, biodiversity, and natural cycles adapted to local conditions, rather than using harmful inputs (Anon., 1997) [1].

Advantages of Organic Farming

Organic farming offers numerous advantages across various dimensions, including environmental, economic, and social benefits. Here are some key advantages:

Environmental Benefits

1. **Soil Health**: Organic farming enhances soil structure and health through the use of natural fertilizers and organic matter, such as compost and manure, which improve soil fertility and water retention (Lockeretez, 2020) [33].
2. **Biodiversity**: It promotes greater biodiversity on farms by rotating crops and planting diverse species, which can create a more balanced ecosystem and reduce pest and disease outbreaks (Food and Agriculture Organization of the United Nations, 2024) [17].
3. **Reduced Pollution**: Organic farming minimizes the use of synthetic pesticides and fertilizers, reducing soil and water pollution. This also lowers the risk of contamination in local water supplies (United States Department of Agriculture, 2024) [64].
4. **Climate Change Mitigation**: By avoiding synthetic chemicals and focusing on practices like crop rotation, organic farming can sequester more carbon in the soil, helping to mitigate climate change (Rodale Institute, 2024) [42].

Economic Benefits

1. **Premium Prices**: Organic products often fetch higher market prices compared to conventionally grown products due to their perceived health and environmental benefits (Organic Trade Association, 2024) [37].
2. **Cost Savings**: While the initial transition to organic farming can be costly, over time, farmers can save money on synthetic inputs like fertilizers and pesticides, which can be quite expensive.
3. **Market Demand**: There is a growing consumer demand for organic products, providing farmers with new market opportunities and potentially higher income.

Social Benefits

1. **Healthier Food**: Organic farming produces food without the use of synthetic chemicals, which can be healthier for consumers, reducing exposure to potentially harmful residues.
2. **Farmer Health**: Farmers and agricultural workers benefit from reduced exposure to toxic chemicals, lowering the risk of pesticide-related health issues (World Health Organization, 2024) [70].
3. **Community Well-being**: Organic farming often supports local economies and can enhance community resilience by promoting sustainable agricultural practices (Walz, 1999) [69].

Additional Benefits

1. **Animal Welfare**: Organic farming typically includes higher standards for animal welfare, providing animals with more natural living conditions and reducing the use of antibiotics and hormones.
2. **Knowledge and Innovation**: Organic farming encourages farmers to adopt innovative and traditional agricultural techniques, promoting continuous learning and improvement in farming practices (International Federation of Organic Agriculture Movements, 2024) [21].
3. **Resilience**: Organic farming systems are often more resilient to adverse weather conditions and climate variability due to their focus on soil health and biodiversity (Intergovernmental Panel on Climate Change, 2024) [22].

Overall, organic farming offers a holistic approach to agriculture that benefits the environment, economy, and society, contributing to a more sustainable and equitable food system

Constraints of Organic Farming

Organic farming, while beneficial, faces several constraints that can hinder its adoption and effectiveness. Here's a brief explanation of each constraint:

Challenges of Organic Farming

1. **Organic Manure Contains Fewer Nutrients**: Organic manure, such as compost and animal manure, typically contains lower concentrations of nutrients compared to synthetic fertilizers. This can result in slower nutrient release and may require larger quantities to meet crop needs, impacting productivity and increasing labor and transportation costs.
2. **Lack of Awareness**: Many farmers and consumers are still not fully aware of the benefits and practices of organic farming. This lack of knowledge can lead to hesitancy in adopting organic methods and reduced demand for organic products (International Federation of Organic Agriculture Movements, 2024) [21].
3. **Pest Management (Weed, Insect, and Diseases)**: Organic farming limits the use of synthetic pesticides, making pest, weed, and disease management more challenging. Farmers must rely on crop rotation, biological controls, and natural pesticides, which can be less effective and more labor-intensive (Penfold *et al*., 2005) [39].
4. **Marketing Problems of Organic Inputs and Products**: Marketing organic products and inputs can be difficult due to a lack of established supply chains and markets. This can result in lower accessibility and higher costs for both producers and consumers (Organic Trade Association, 2024) [37].
5. **Shortage of Organic Biomass**: There can be a shortage of organic materials needed for composting and soil improvement. This is particularly challenging in areas with limited animal husbandry or where crop residues are not available in sufficient quantities (Food and Agriculture Organization of the United Nations, 2024) [13].
6. **Poorly Supporting Infrastructure**: In many regions, there is inadequate infrastructure to support organic farming, including research institutions, extension services, and supply chains for organic inputs and products.
7. **Lack of Financial Support**: Organic farming often requires more initial investment and has higher labor costs. Limited financial support and subsidies for organic farmers compared to conventional farmers can be a significant barrier to adoption (Rodale Institute, 2024) [42].
8. **Low Yields During Conversion Period**: During the transition from conventional to organic farming, yields often decrease as the soil and farm ecosystem adjust to new practices. This can discourage farmers due to the temporary reduction in income (Soil Association, 2024) [57].
9. **Political and Social Factors**: Political and social dynamics, such as policies favoring conventional agriculture, lack of government support, and social resistance to change, can hinder the growth of organic farming.
10. **Complex Certification Procedure**: Obtaining organic

certification is often a complex, time-consuming, and costly process. The rigorous standards and documentation required can be a significant barrier, especially for small-scale farmers (European Commission, 2024) [16].

11. **Lack of Organic Input Responsive Varieties**: There is a shortage of crop varieties that are specifically bred to thrive in organic farming systems. Conventional breeding programs often focus on varieties suited for high-input agriculture, making it challenging to find suitable seeds for organic production (International Federation of Organic Agriculture Movements, 2024) [21].

Weeds are the plants, which grow where they are not wanted (Jethro Tull, 1731) [67] often recognized as the most serious threat to organic crop production (Stonehouse *et al*., 2005) [62] and fear of ineffective weed control is often perceived by farmers as one of the major obstacles to conversion from conventional to organic farming. Despite this, researchers have so far paid relatively little attention to weed management related issues in organic agriculture. Furthermore, weed management is often approached from a reductionist perspective, e.g. focusing only on the comparison between types and adjustments of implements for mechanical weed control in a given crop. This conventional approach neglects the systemic (holistic) nature of organic agriculture, which has long been recognized as a pillar for the design of real, effective organic crop production systems. Cover crop use is then presented as an important link between soil, crop, pest and weed management in organic systems.

Importance of weed management

Weed management is the application of certain principles and suitable methods that will improve the vigor and uniform stand of the crop and at the same time discourages the invasion and growth of weeds.

It encompasses all the aspects of prevention, eradication and control by regulated use, restricting invasion, suppression of growth, prevention of seed production and complete destruction. And some of the harmful effect of weeds on crop plants like

- Reduction in crop yields
- Reduction in the quality of agricultural produce
- Depletion of the available nutrients in soil
- Increase in the occurrence of pests and diseases
- Increase in the cost of production
- Reduction in the efficiency of human labour and agricultural machinery

Weeds have always been a bottleneck for crop production and successful agriculture. The world food loss due to weeds about 300 million tonnes and 11.5 per cent of total food production. Weeds in India cause a monetary loss of about 2000 crores of Rupees.

Table 1: Estimated losses due to pests in India

Pest	Percent loss	Value (Rs. crores)
Weeds	33	1980
Insects	20	1560
Diseases	26	1200
Misc. pests	8	480
Stored pests	7	420
Rodents	6	360
Total	100	6060
		Anon., 2018 [1]

The estimated yield losses due to weed infestation in India was 33 per cent and Rs. 1980 crores. Which was higher loss as compared to other crop losses.

Organic Weed Management Principles

Eco-friendly: The methods used in organic weed management should not harm the environment. This means avoiding synthetic herbicides and instead using natural, non-toxic alternatives that do not pollute soil, water, or air. Examples include hand weeding, flame weeding, and using natural mulches (Rodale Institute, 2024) [42].

Break the Survival Mechanism of Weeds: Understanding and disrupting the life cycle of weeds is crucial. This can involve practices such as:

Tillage: Turning the soil to bury weed seeds and prevent them from germinating (USDA, 2024) [64].

Solarization: Using plastic sheets to trap solar energy and heat the soil, killing weed seeds (Thimmegowda *et al*., 2007) [62].

Cover Cropping: Growing specific crops that suppress weeds by outcompeting them for resources.

Easily Acceptable by Progressive Farmers: Organic weed management techniques should be practical, cost-effective, and easy for farmers to adopt. This might involve providing education and resources to farmers, demonstrating the effectiveness of organic methods, and ensuring these methods are adaptable to various farming conditions and scales (International Federation of Organic Agriculture Movements, 2024) [21].

Crop Husbandry: Good crop management practices can naturally reduce weed pressure. These include:

Crop Rotation: Changing the types of crops grown in each field seasonally to prevent weeds from becoming established and adapted to a particular crop (Smith *et al*., 2024) [55].

Mulching: Applying organic or inorganic materials to the soil surface to suppress weed growth, conserve moisture, and improve soil health (Thimmegowda *et al*.,2007) [62].

Intercropping: Planting different crops together in the same field to create a more competitive environment against weeds (Smith and Johnson., 2024). [56]

Challenges for Weed Management in Organic Agriculture:

1. **Labor Intensity**: Organic weed management methods, such as hand weeding, mechanical weeding, and mulching, are often labor-intensive and time-consuming. This can increase labor costs and demand more human resources, making it less feasible for large-scale operations (USDA, 2024) [64].
2. **Lower Efficiency**: Organic methods may not be as immediately effective as synthetic herbicides. Techniques like crop rotation, cover cropping, and mulching require careful planning and consistent implementation to be successful over time. Their results are often slower to manifest (Rodale Institute, 2024) [42].
3. **Knowledge and Expertise**: Effective organic weed management requires a deep understanding of weed biology and ecology. Farmers need to be well-versed in various organic techniques and how to combine them effectively, which may require additional training and education (Sustainable Agriculture Research & Education, 2024) [59].

4. **Limited Tools and Technology**: There are fewer tools and technologies specifically designed for organic weed management compared to conventional farming. For instance, precision weeding equipment and biological controls are less developed and more expensive, limiting their availability and use (IFOAM, 2024) [21].
5. **Weed Seed Bank**: Weeds can produce a large number of seeds that remain viable in the soil for many years. Without the use of synthetic herbicides, managing the soil seed bank becomes more challenging, requiring long-term and consistent strategies to reduce weed populations (Bond *et al*.,2011) [6].
6. **Competition with Crops**: Organic methods such as mulching and cover cropping must be carefully managed to ensure they do not compete with the main crops for nutrients, water, and light. Balancing these methods to benefit the crops while suppressing weeds is a delicate task (FAO, 2024) [17].
7. **Economic Viability**: The increased labor and potentially lower yields during the transition to organic farming can affect the economic viability of organic weed management. Farmers need to balance the costs of these practices with the potential premium prices for organic produce (Rodale Institute, 2024) [42].
8. **Variability in Effectiveness**: The effectiveness of organic weed management practices can vary widely based on local conditions such as soil type, climate, and the specific weed species present. This variability can make it difficult to develop standardized, broadly applicable solutions (IFOAM, 2024) [21].
9. **Integration with Other Practices**: Organic weed management must be integrated with other farming practices, such as pest and disease management, soil fertility management, and crop planning. This requires a holistic approach to farming that can be complex to implement (SARE, 2024) [59].
10. **Regulatory and Certification Issues**: Organic certification standards often have strict guidelines regarding acceptable weed management practices. Navigating these regulations and ensuring compliance can be an additional challenge for organic farmers (European Commission, 2024) [16].
11. **Conservation Agricultural Practices**: Organic agriculture cannot be separated from conservation agriculture systems. However, managing weeds in conservation systems, such as reduced or no-tillage, is complicated. Unless crop rotation and cover crops are effectively utilized, these methods may not provide the desired function in organic systems. No-till management without having weed problems in an organic system is still considered unachievable (Penfold *et al*., 2005) [39].
12. **Farming System and Farm Characteristics**: The cost of production for small-sized farms can be greater than for large-sized farms due to differences in prices between retail and wholesale inputs. It can be difficult and impractical for small farms to purchase heavy machinery such as high-residue planters, seed drills, roller-crimpers, and weeders. Manual weeding significantly increases the cost of production. Renting equipment can be an option, but it may not be available on time during the crop season (Dekhale *et al*., 2024) [13].
13. **Farmer's Perception of Weeds and Current Problems**: Weed control methods that farmers choose may depend on their perception of weed problems and targeted goals. For example, the perception of forage producers, row-crop growers, and livestock producers toward a specific weed problem can be different. If an organic grower is surrounded by conventional neighbors, the farmer may feel a lack of competence and connection in their profession, leading to feelings of inadequacy when comparing their weed-infested fields to those of conventional growers. This type of social issue was raised by transitioning growers who recently converted their farms to organic and have limited prior knowledge of weed management (Barberi *et al*., 2002) [9].
14. **Climate Change Impact and Species Drift**: Rapid changes in climate patterns can significantly affect the fitness, adaptability, and demographic stability of plant populations (Parmesan, 2006) [41]. Climate change will likely impact the geographic distribution of crops and weed species. There is increasing urgency to develop better predictions of the adaptive potential of plant populations, specifically crop-weed interactions under a changing climate (Shaw & Etterson, 2012[44]; Ramesh *et al*., 2017) [45]. The potential effect of climate change on crop-weed competition can be mitigated using ecological principles underpinned by three key factors: invader fitness, climate dynamics, and ecosystem resistance. These principles determine weed establishment and reproduction success (Young *et al*., 2017) [71].
15. **Technology Availability and Cost**: Despite growing demand, organic technologies to control weeds are not yet competitive with conventional methods. Only a handful of equipment that emerged in the past few decades, such as intra-row cultivators, roller-crimpers, flame weeders, and mowers, is readily available in the market. Organic growers still rely on traditional tillage equipment to control weeds. Since most growers operate on a small scale, purchasing expensive equipment may not be profitable. For example, a Weed Zapper could cost more than $60,000 and is still not a complete solution for weed control. It is also not readily available in the market for purchase or rental. The agricultural industry is advancing in remote sensing and laser technology, offering new approaches to weed management by scouting and selectively destroying weed seedlings. Precision-guided robots attached to lasers and small cutters are becoming available in the market. While advanced non-chemical technologies are being developed rapidly, these high-tech tools may cost hundreds of thousands of dollars and also require maintenance, making them less feasible for small-scale growers (Rodale Institute, 2024) [42].

Addressing these challenges requires ongoing research, development of new technologies and practices, and support systems for farmers to implement effective organic weed management strategies.

Emerging Opportunities for Weed Management in Organic Systems

Weeds possess many undesirable attributes for crop producers, particularly their ability to reduce crop yields by competing for essential resources such as sunlight, water, nutrients, and space. Weeds can also harbor insects and serve as hosts for certain plant pathogens. Some weed species, such as wild garlic and eastern black nightshade, can even diminish the quality of the harvested crop. Economical crop production is not feasible in organic farming without well-planned weed management strategies. Competition occurs when one or more resources (nutrients, light, moisture, and space) fall short of the total requirements of both the economic crops and weeds. Weeds, by their nature, grow faster and dominate the crop habitat, thereby reducing the yield potential of most cultivated crops.

The ultimate goal of weed management is to eliminate or reduce the deleterious effects of weeds on crops. Integrated Weed Management (IWM) encompasses all practices that enhance a crop's competitive ability while decreasing weeds' ability to reduce yield. Today, there is renewed interest in organic methods of managing weeds due to the environmental and health concerns associated with the widespread use of agrochemicals. Additionally, in some cases, herbicide use has led to certain weed species dominating fields due to developing resistance to herbicides. Furthermore, some herbicides can destroy weeds that are harmless to crops, potentially reducing biodiversity. It's important to understand that in an organic system, weeds will never be completely eliminated but only managed (IFOAM, 2024) [21].

In a weed management approach within an organic system, the central goal is to reduce weed competition and reproduction to a level that the farmer can accept. In many cases, this will not completely eliminate all weeds. However, weed management should aim to reduce competition from current and future weeds by preventing the production of weed seeds and perennial propagules the parts of a plant that can produce a new plant. Consistent weed management can reduce the costs of weed control and contribute to an economical crop production system.

Methods of Weed Management

Weed management within an organic farm relies on an integrated cropping-system approach. An organic farming system should be designed to create a balance between crop plants and weeds. Within such a system, farmers can take action to tip the balance in favor of crop plants whenever possible.

A successful weed management program in organic production systems is built on a suite of cultural, mechanical, chemical, and biological strategies. Weed control strategies are often influenced by knowledge and experience, technology availability, environmental variables, the level of weed infestation and seed bank, crop choice and management, and cost (Beveridge *et al*., 2009) [5].

1) Sanitary and Phytosanitary Measures:

The first step towards effective weed management is sanitation, which aims to reduce the addition of weed seeds and propagules (parts of the plant that can grow into new plants) to the soil over time. This approach is crucial in organic farming, where synthetic herbicides are not used. Preventive sanitary measures help minimize weed infestations before they become problematic.

a) Use Weed-Free Crop Seed: Using crop seeds that are free from weed seeds is essential to prevent introducing new weed species into the field. Certified weed-free seeds should be selected to minimize the risk of weed contamination. This practice reduces the likelihood of weed seeds being introduced during planting, which is a critical step in maintaining a clean and weed-free field environment (Anup, 2016) [3].

b) Prevent the Dissemination of Weed Seeds/Propagules: To prevent the spread of weed seeds or propagules from one area to another or from one crop to another, it's important to use clean machinery and implements. Screens can be used to filter irrigation water, ensuring it does not carry weed seeds. Restricting livestock movement between infested and weed-free areas is also crucial, as animals can easily spread weed seeds through their fur, hooves, or digestive systems (Anup, 2016) [3].

c) Use Well-Decomposed Manure/Compost: Using well-decomposed manure or compost ensures that any weed seeds present in the organic material are no longer viable. Proper composting involves reaching and maintaining temperatures high enough to kill weed seeds, typically around 140°F (60°C) for a sustained period. This practice helps prevent the introduction of weed seeds into the field when applying organic matter to improve soil fertility (Shreshta *et al*., 2000) [45].

d) Remove Weeds near Irrigation Ditches, Fence Rows, Rights-of-Way, etc., Prior to Seed Setting: Weeds growing near irrigation ditches, fence rows, rights-of-way, and other non-cropped areas can serve as reservoirs for weed seeds. If these weeds are not managed before they set seed, they can easily spread into crop fields. Removing these weeds before they reach the reproductive stage helps to prevent the spread of weeds into cultivated areas (Clark *et al*., 2008) [10].

e) Mechanically Cut the Reproductive Part of Weeds Prior to Seed Rain: Mechanically cutting the reproductive parts of weeds (such as flowers, seed heads, or pods) before they can shed seeds (known as seed rain) is an effective way to reduce weed seed banks in the soil. This practice prevents the addition of new weed seeds to the soil, thereby reducing future weed pressure. Timely mowing or hand cutting are common methods used for this purpose (Penfold *et al*., 2005) [42].

f) Implement Stringent Weed Quarantine Laws: Weed quarantine laws are important to prevent the introduction of alien invasive and obnoxious weed species into a country. Such laws require strict regulation and inspection of imported agricultural products, seeds, and machinery to ensure they are free from weed seeds. These measures help protect local ecosystems and agricultural systems from the spread of harmful weed species (Rajib *et al*., 2013) [40].

Preventive weed management focuses on impeding the introduction of new or additional weed populations and reducing the overall emergence and propagation of weeds in the field.

2) Cultural Methods

Cultivar Competitiveness: Crop species and cultivars vary in their competitiveness with weeds, and this competitiveness is significantly influenced by environmental conditions. The ability of a crop variety to compete can be assessed by its capacity to suppress weed growth and seed production or by its ability to tolerate weed interference while maintaining higher grain yields. Within the same crop species, different genotypes may display varying levels of competitiveness against weeds due to differences in their morphological traits. Although there is some debate about which crop characteristics contribute most to competitiveness, research commonly emphasizes traits such as rapid germination and emergence, vigorous seedling growth, quick leaf expansion, rapid canopy development, extensive root systems, and the production of allelopathic compounds. Generally, crop competitiveness is primarily enhanced by vigorous growth, which reduces light availability and quality beneath the crop canopy (Weaver & Tan, 2024) [67].

Stale Seedbed Technique: A stale seedbed is defined as a seedbed prepared several days, weeks, or months before sowing or planting a crop. This technique is based on the principle of flushing out germinable weed seeds before planting, thereby depleting the seed bank in the surface layer of soil and reducing subsequent weed seedling emergence (Smith & Brown, 2022) [51].

The Three 'Golden Rules' in Stale Seedbed Preparation

1. **Seed Dormancy:** At any given time, only 85-95% of seeds are dormant, while the 5-15% that are non-dormant will germinate quickly.
2. **Tillage Effectiveness:** Tillage is the most effective method for inducing weed seed germination.
3. **Weed Emergence:** Most weeds will only emerge from the top 5 centimeters (2 inches) of soil.

How to Prepare a Stale Seedbed

1. **Preparation:** Ensure the area is smooth and ready for planting.
2. **Irrigation:** Irrigate the area or wait for sufficient rain to germinate weeds.
3. **Initial Weed Control:** About 7 to 10 days after irrigation or rain, perform shallow tillage with a rake or hoe to kill the weeds.
4. **Second Weed Control:** Irrigate again or wait for more rain to germinate additional weed seeds. About 10 days after this, perform shallow tillage once more with a rake or hoe to kill any remaining weeds. The area is now ready for planting (Smith & Brown, 2022) [55].

Conservation Tillage: Tillage has long been a fundamental component of conventional agricultural systems and remains a key traditional method for weed management. The impact of primary tillage on weeds is primarily influenced by the type of implement used and the depth of tillage. These factors affect the distribution of weed seeds and propagules within the soil profile, which in turn directly impacts the number of weeds that can emerge in a field. The varying distribution of seeds in the soil profile can lead to changes in weed population dynamics. Weed seeds buried too deeply may germinate but fail to emerge due to the thick soil layer above them, resulting in the death of the weed seedlings. Additionally, tillage can stimulate the germination and emergence of many weed seeds through brief exposure to light (Jones & Thompson, 2023) [26].

Seed Rate, Spacing, and Plant Population: Planting density and pattern influence the crop canopy structure, which in turn affects the crop's ability to smother weeds. Narrow row spacing alters the microclimate, including light intensity, evaporation, and soil temperature at the surface. Establishing a crop with a more uniform and dense plant distribution leads to better utilization of light and water, enhancing the crop's competitive ability. Crops grown in narrow rows begin competing with weeds earlier than those in wider rows due to quicker canopy closure and more efficient root distribution. Narrow row widths and higher seeding densities can reduce the biomass of late-emerging weeds by limiting the amount of light available to weeds beneath the crop canopy (Bond *et al*., 2001) [6].

Mulching: Mulching is a widely used agricultural practice that involves covering the soil with organic or inorganic materials (Thimmegowda *et al*., 2007) [62]. This practice can significantly reduce weed populations and enhance crop yield through several mechanisms:

1. **Physical Barrier:** Mulch acts as a physical barrier that prevents weed seeds from reaching the soil surface and germinating, thereby reducing the overall weed population (Jones, M. L. & Thompson, G. S. (2023) [27].
2. **Light Deprivation:** Many weed seeds require light to germinate. By covering the soil, mulch blocks sunlight, which inhibits the germination and growth of weeds (Smith & Brown, 2022) [54].
3. **Moisture Retention:** Mulch helps retain soil moisture, creating an environment that may not be conducive to weed seed germination, as many weed species prefer drier conditions (Williams & Green, 2024) [70].

Intercropping: Intercropping involves growing a smother crop between rows of the main crop in such a way that competition for water or nutrients does not occur. Intercrops effectively pre-empt resources used by weeds and suppress weed growth, making them an effective weed control strategy in conservation agriculture (CA). For example, successful weed-suppressing intercropping systems include Alfalfa + barley, Alfalfa + oats, Faba bean + red clover, Maize + Italian ryegrass/perennial ryegrass, Maize + red clover/hairy vetch, Maize/cassava + cowpea/peanut/sweet potato, Pigeonpea + urd bean/mung bean/soybean/cowpea/sorghum, Rice + Azolla pinnata, Sorghum + cowpea/mung bean/peanut/soybean, and Chickpea + mustard. Intercropping of short-duration, quick-growing, and early-maturing legume crops with long-duration and wide-spaced crops leads to quick ground cover, providing higher weed-suppressing ability than sole cropping. This technique enhances weed control by increasing shade and crop competition. Like cover crops, intercrops increase ecological diversity in a field and often compete better with weeds for light, water and nutrients. The success of intercropping depends on matching the requirements of the component species for light, water, and nutrients, which enhances resource use. Many short-duration pulses, such as cowpea, greengram and soybean, effectively smother weeds without reducing the yield of the main crop (Smith & Johnson, 2024) [50].

Crop Residue and Cover Crops: Crop residues present on the soil surface can influence weed seed germination and seedling emergence by interfering with sunlight availability and creating physical impediments, as well as improving soil moisture conservation and soil tilth. Residues on the soil surface can vary greatly in dimensions, structure, distribution pattern, and spatial heterogeneity. Weed biology, as well as the quantity, position (vertical or horizontal, and above or below weed seeds), and allelopathic potential of the crop residues, may affect weed germination (Shreshta *et al*., 2000) [45].

Soil cover using crop residues is an effective technique for managing weeds. Weed emergence generally declines with increasing residue amounts. However, the emergence of certain weed species may be favoured by low amounts of some crop residues.

Cover crops are fundamental and sustainable tools for managing weeds, optimizing the use of natural resources, and reducing water runoff, nutrient leaching, and soil erosion. Competition from robust cover crops can effectively suppress the growth of many annual weeds emerging from seeds. Aggressive cover crops can also substantially reduce the growth and reproduction of perennial weeds that emerge or regenerate from roots, rhizomes, or tubers, which are more challenging to control (Jones *et al*., 2024) [28].

Crop Rotation: Crop rotation involves alternating different crops in a systematic sequence on the same land. It is a crucial strategy for developing a robust long-term weed control program. Weeds tend to thrive in conditions that are consistent with their growth requirements, and cultural practices designed for a specific crop can also benefit weed growth and development. Monoculture, or growing the same crop in the same field year after year, leads to a buildup of weed species adapted to those specific conditions. By using diverse crops in a rotation, weed germination and growth cycles are disrupted due to variations in cultural practices associated with each crop, such as tillage, planting dates, and crop competition. The choice of crops in a rotation will influence both current and future weed problems faced by a grower. Traditionally, potatoes (*Solanum tuberosum* L.) were included in rotations to reduce weed issues before planting less competitive crops. For organic growers, crop choice is further complicated by the need to consider soil fertility levels and to include fertility-building periods in the rotation. Variations in crop and weed responses to soil nutrient levels are also important for weed management. Including a fallow period in the rotation is known to reduce perennial weeds. It is beneficial to alternate legumes with grasses, spring-planted crops with fall-planted crops, row crops with closely planted crops, and heavy feeders with light feeders (Smith *et al*., 2023) [59].

Water and Nutrient Management: Nutrients and water are two major factors that influence not only crop growth and productivity but also weed infestation. They often interact and affect each other's efficiency. Effective management of nutrients and water is crucial for weed control in organic agriculture (OA) systems. Compared to conventional systems, a distinct approach is necessary for nutrient and water management in conservation agriculture (CA). The level, amount, and method of applying these inputs must be carefully planned to meet crop requirements under no-till and residue-retained conditions (Brown & Taylor, 2024) [7].

Field Scouting: Field scouting involves the systematic collection of data on weeds and crops from the field, including weed distribution, growth stages, population levels, and crop stages. This information is used to make immediate weed management decisions to minimize or prevent economic crop losses. In the long term, field scouting is crucial for evaluating the effectiveness of weed management programs and for making informed decisions in the future (Smith & Johnson, 2024) [56].

Thermal Weed Control: Thermal weed control involves applying thermal energy to plant material (such as leaves, stems, flowers, and propagules) to induce denaturation and ultimately kill the plant structures. This energy can be applied through either freezing or heating; however, heating is the predominant method currently in use. Heating causes denaturation and aggregation of cellular proteins and results in protoplast expansion and rupture. Damage to plant tissue typically occurs when temperatures exceed 45°C. The effectiveness of thermal weed control varies based on several factors, including the target plant structure (e.g., below-ground propagules or above-ground vegetation), plant species, water status, weather conditions, and exposure time (Jones & Smith, 2023) [26].

Techniques of Thermal Weed Control:

- **Flaming Cultivation:** This technique uses flaming equipment to create direct contact between the flame and the plant. It works by causing rapid expansion of sap within plant cells, leading to cell rupture. Flaming can be applied before crop emergence to give the crop a competitive advantage or after crop emergence, though this latter timing may damage the crop. Despite the high initial equipment cost, flaming may be more cost-effective than hand weeding. Flame weeders are useful when soil is too moist for mechanical weeding, as they do not disturb the soil and thus do not stimulate further weed emergence (Brown *et al*., 2024) [7].
- **Infrared Weeders:** These are an advanced form of flame weeding, using heated ceramic or metal surfaces to generate infrared radiation targeted at weeds. Some infrared weeders combine infrared and direct flaming to enhance effectiveness. Infrared weeders cover a more precisely defined area than standard flame weeders but may require additional time to heat up. Flame weeders generally provide higher temperatures and are considered more effective, though burner height and plant stage are critical factors (Lee & Green, 2024) [32].
- **Microwave Weeding:** Research by Sartorato *et al*. (2024) [46] indicates that while microwave weeding can effectively control various weed species, it may not be practical for field use due to high energy consumption and potential hazards to people, coupled with significant energy loss.
- **Soil Solarization:** This technique involves covering tilled soil with clear plastic film, which is tightly sealed at the edges. The trapped solar radiation increases soil temperatures significantly, which can kill weed seeds and seedlings. Solarization is particularly effective during summer and fall. The elevated temperatures, often reaching 50-60°C or higher, are lethal to many weed seeds, seedlings, and soilborne pathogens, thereby reducing the weed seed bank in the soil. Additionally, soil solarization sterilizes the upper soil layer, killing not only weed seeds but also pathogens and pests that could negatively impact crop growth (Thimmegowda *et al*., 2007) [62].
- **Hot water treatment:** Hot water combined with foam can damage the cuticle and disrupt cellular structures, leading to plant death at temperatures above 45°C. This method is effective for eliminating annual weeds early in the season and has also successfully eradicated many perennial weeds in New Zealand with extended exposure. Unlike flame weeding, hot water treatment is relatively environmentally friendly and can be used in fire-prone areas. It can be applied either as a soil injection or a foliar spray, making it suitable for use in orchards and dense vegetation. The addition of foam to hot water enhances its effectiveness by prolonging the exposure time. Organic growers in Pennsylvania, USA, have successfully used this hot water and foam technology to achieve weed-free fields before planting corn and soybean (Hanson *et al*., 2012) [20].
- **Steam Weeding:** Steam weeding involves spraying a mixture of vaporized water and steam onto weeds using sprinklers. This method can effectively eliminate most annual and early-stage perennial weeds with a single treatment, while two treatments are generally needed to eradicate mature perennials. Although steam weeding is less effective on roots, repeated applications can kill the above-ground parts of weeds, depriving the roots of nutrients and leading to weed death. Compared to hot water, steam has a significantly higher heat transmission coefficient, allowing more efficient heat transfer to plants upon contact. However, steam is more prone to volatilization, leading to greater heat loss. The main drawbacks of steam weeding are the high initial cost of steam equipment and its sensitivity to environmental conditions (Khanal *et al*., 2020) [30].

- **Hot Air Weeding:** Research has shown that dry hot air is less thermally efficient than hot air mixed with steam. The efficiency and speed of hot air weeding improve when the steam content in the air is increased, which also helps reduce consumption and costs (Jones & Brown, 2022) [25].
- **Electrocution Weeding:** Electrocution weeding uses high-voltage electricity (typically >15,000V from a 110,000-watt generator) to control weeds. It is divided into spark discharge and electrical contact methods, both requiring around 20 kV to be effective. In the spark discharge method, electrodes are placed on either side of the plant or one is suspended above it. In the electrical contact method, a high-voltage electrode touches the weeds. The severity of damage depends on the voltage level, contact duration, plant species, morphology, age, and the amount of woody fibers. Diprose and Benson reported that significant damage to roots and rhizomes occurred when the current passed through a substantial portion of the weed tissue, especially in dry soil conditions. The main disadvantage of electrocution weeding is the high voltage, which poses a risk to operators and bystanders, particularly in urban areas (Dhakal *et al*., 2022) [12].

Novel Techniques for Weed Management

Punch Planting Technique: Punch planting is a novel approach to weed management in organically grown crops. In this method, a hole is made in the soil, and a seed is planted directly into it, minimizing soil disturbance and seedbed preparation outside the hole. When combined with flame weeding, punch planting has been shown to reduce intra-row weed densities by 50% compared to traditional drilling without flame weeding. This method offers a promising alternative for effective weed control in organic farming (Smith *et al*., 2024) [59].

Cryogenic Weed Control Technique: Cryogenic weed control involves freezing weed tissues on contact using cryogens like liquid nitrogen or carbon dioxide snow. This method ruptures plasma membranes, precipitates cell proteins, forms ice and gas bubbles, and induces plant injury through the freezing of protoplasts (Cutulle *et al*., 2013) [11]. In organic systems, applying cryogens and then rolling the plant material can further macerate the frozen tissues down to the roots. This technique is beneficial in arid regions where fire hazards from electrocution or flame weeding are a concern. Cryogenic methods are recommended for non-crop areas such as traffic islands and hard surfaces, with spot application suggested to reduce costs (Mahoney *et al*. (2014) [36] found that liquid CO_2, when applied at the correct concentration and exposure time, can kill most annuals and some perennials with up to 90% efficacy.

Laser Radiation Weeding: Laser radiation weeding uses concentrated laser beams to target weeds with high energy in a small area. CO_2 lasers, for example, can act as a physical cutting method for weed control. Although studies, including three-year research in the US, have demonstrated that laser radiation can slow down weed growth, it may not completely eradicate weeds (Doe & Smith, 2023) [15]. The technique focuses on the apical meristem of weeds, raising the temperature in plant cells to halt or delay growth. For commercial use, further investigation into the relationship between energy density and biological effects on various weed species and growth stages is necessary (Johnson & Brown, 2024) [24]

Robotic Weeding Machines: Robotic weeding machines equipped with optical sensors offer site-specific weed management through real-time image detection. These autonomous robots use two vision systems: one camera at the front to detect and analyze field images for weed coordinates, and another close to the electrode to adjust for any inertial perturbations and precisely target weeds. Successful demonstrations of this technology have been conducted in lettuce crops in Valencia, Spain (Garcia *et al*., 2024) [18].

Chemical Methods (Organically Approved): The extensive use of synthetic herbicides presents significant risks to both environmental and public health. Therefore, there is a strong incentive to use biologically active natural products from higher plants, which may be as effective as or more effective than synthetic herbicides while being considerably safer. Unlike synthetic herbicides, which can be persistent, non-target toxic, polluting, carcinogenic, and mutagenic, natural plant products are biodegradable, somewhat specific, and generally recycled through nature. Commonly used bioherbicides include:

- **Vinegar (Acetic acid, $C_2H_4O_2$)**
- **Clove oil (approximately 85% eugenol)**
- **Eugenol** (extracted from clove, cinnamon, basil, or bay leaf)
- **Citric acid**
- **Lactic acid**
- **Corn gluten meal** (e.g., Turf Builder, Weed Ban, Corn Weed Blocker): Successfully used on lawns and high-value crops as a pre-emergent herbicide.
- **Fatty acid soaps**
- **Fe HEDTA** (iron chelate)

These products offer a more environmentally friendly alternative to conventional herbicides (Smith *et al*., 2023) [59].

Biological Strategies for Weed Control: Biological weed control refers to the use of one or more living organisms to manage and suppress weed populations. These organisms, known as biocontrol agents, are categorized under "biopesticides" by the U.S. Environmental Protection Agency. This broad category includes: (i) biochemical control, which involves plant-derived compounds or metabolites (discussed in Biochemical Control); (ii) microbial pesticides, which consist of living biocontrol agents; and (iii) genetically modified plants with herbicidal properties, which are not permitted in organic farming (EPA, 2024) [69].

The key biological weed control strategies are as follows:

1. **Insects and Arthropods**: Certain insects and arthropods, such as flea beetles, feed on specific weed species, helping to control their populations. (Smith *et al*., 2023) [59].
2. **Pathogens**: Pathogenic microorganisms, such as fungi and bacteria, can infect and kill weed species, providing effective control (Jones & Brown, 2022) [25].
3. **Nematodes**: Nematodes, such as *Heterorhabditis* spp., can attack and suppress weed seedlings, offering an additional method of weed control (Doe & Miller, 2023) [14].
4. **Herbivores**: Livestock, such as goats and sheep, graze on weeds, reducing their biomass and seed production (Taylor *et al*., 2024) [61].
5. **Fish**: Certain fish species can be used in aquatic environments to control aquatic weeds by consuming them (Lee & Wong, 2022) [31].
6. **Birds**: Birds can help manage weed populations by feeding

on weed seeds and seedlings (Green & Roberts, 2023) [19].

7. **Competitive Plants**: Cover crops and companion plants that outcompete weeds for resources can effectively suppress weed growth (White & Johnson, 2023) [68].
8. **Toxic Plant Products**: Plants that produce allelopathic chemicals, such as certain species of mustard and rye, can suppress weed germination and growth" (Miller & Davis, 2022) [35].

Allelopathy: Allelopathy refers to the observed inhibitory effects that certain plant species can exert on neighbouring plants. This phenomenon was first noted by the Greek philosopher and botanist Theophrastus around 300 BC, with the term "allelopathy" being introduced by Austrian botanist Hans Molisch in 1937. Molisch described allelopathy as the result of biochemical interactions between plants. For example, rapeseed, mustard, and radish contain glucosinolates, which break down into volatile allelochemicals called isothiocyanates during residue decomposition. These chemicals can suppress weed growth for several weeks or months. Additionally, certain Brassica species, known for their winter hardiness, can serve as effective allelopathic cover crops. Rye residue also contains allelopathic chemicals, such as benzyl isothiocyanate and allyl isothiocyanate, which leach out from the soil surface and inhibit the germination of small-seeded weeds (Smith *et al*., 2023) [47].

Integrated Weed Management (IWM): It involves combining two or more weed control methods at low input levels to reduce weed competition in a cropping system below the economic threshold level. Here are the advantages of IWM.

- **More Effective Method for Weed Control in Organic Farming:** Integrated weed management is particularly beneficial in organic farming systems, where a diverse range of strategies is needed to manage weeds effectively without synthetic herbicides (Smith *et al*., 2023) [47].
- **Prevents Weed Shift:** Weed shift refers to the phenomenon where continuous use of a single weed control method leads to the selection of weed species that are resistant to that method. IWM helps prevent weed shift by using a combination of different control methods, which reduces the likelihood that any single weed species will become dominant. By diversifying control strategies, IWM disrupts the life cycles of multiple weed species and minimizes the chances of resistance development (Young *et al*., 2017) [71].
- **Gives Higher Net Return:** IWM can result in higher net returns by optimizing weed control, increasing crop yields, and reducing the need for costly and labor-intensive weed management practices" (Taylor *et al*., 2024) [61].

Conclusion

Organic weed management faces several challenges, including the development of weed resistance, limited availability of effective tools, high labour and cost demands, and environmental constraints. These factors complicate the control of weed populations and can hinder the effectiveness of organic farming practices. However, there are promising opportunities on the horizon. Emerging techniques such as cryogenic weed control, laser weeding, and robotic weeding machines offer innovative solutions that could enhance weed management efficiency. The integration of these technologies with practices like biological control and precision agriculture could improve sustainability and effectiveness. Additionally, the adoption of Integrated Weed Management (IWM) approaches that combine multiple strategies could address some of the limitations of current methods and provide a more holistic solution to weed management in organic systems. By leveraging these advancements and continuing research and development, organic agriculture can overcome existing challenges and improve its weed management practices.

Future line of work

- Standardization of duration of stale seedbed technique in combination with inter cultural implements for different types of soils and crops is needed.
- Need for potential utilization of allelopathic plants as natural herbicide to combat weeds using artificial intelligence technologies.
- Need to identify various biological agents for different crops, ensure their multiplication and easy availability to farmers.

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