Plant Archives Vol. 26, No. 1, 2026 pp. 1085-1095 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.1.148

INTEGRATED WEED MANAGEMENT STRATEGIES IN VEGETABLE CROPS: A COMPREHENSIVE REVIEW

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(Date of Receiving-25-11-2025; Date of Revision-28-12-2025; Date of Acceptance-03-02-2026)

ABSTRACT

Weeds cause significant yield losses, worse produce quality, and higher production costs, making them one of the most significant biotic restrictions limiting vegetable crop production globally. Due to their wide spacing, slow initial development, and extensive management techniques, vegetable crops are especially susceptible to weed competition. Herbicide resistance, environmental damage, and health concerns are only a few of the issues brought on by an over-reliance on chemical herbicides for weed management. In this regard, Integrated Weed Management (IWM), which integrates several weed management techniques to achieve efficient and long-term weed suppression, has emerged as a sustainable and environmentally beneficial method. The relevance of combining cultural, mechanical, physical, biological, and chemical treatments based on weed ecology and cropping systems is emphasised in this review, which offers a thorough synthesis of integrated weed management strategies in vegetable crops. The important period of weed competition and its effects on crop growth and productivity are highlighted in the paper's discussion of weed flora and ecological dynamics in vegetable fields. The role of cultural methods like mulching, cover crops, crop rotation, and planting geometry in reducing weed emergence and enhancing crop competitiveness is examined. Hand weeding, inter-row cultivation, burning, and soil solarisation are examples of mechanical and physical techniques that are assessed as non-chemical substitutes appropriate for vegetable production systems. The prudent application of herbicides within an IWM framework is given particular attention, with a focus on resistance management techniques, herbicide selectivity, and mode of action rotation. Promising tools for sustainable vegetable production are also highlighted, including robotic weed control, sensor-based technology, and precision weed management. The review comes to the conclusion that using integrated weed control techniques in vegetable cropping systems can lessen reliance on herbicides, postpone the emergence of herbicide resistance, increase financial returns, and support environmental sustainability. For IWM to be successfully implemented in a variety of agro-ecological zones, research, extension, and farmer awareness must be strengthened.

***Key words*:** Integrated weed management, Vegetable crops, Weed ecology, Cultural practices, Mulching, Cover crops, Mechanical weeding, Herbicide resistance, Precision farming, Sustainability

Introduction

As they supply vital vitamins, minerals, dietary fibre, and antioxidants, vegetable crops are vital to the world's food and nutritional security. However, because of frequent irrigation, high fertiliser inputs, increased row spacing, and slow initial crop growth, vegetable production systems are extremely vulnerable to weed invasion. Vegetable crops face intense competition from weeds for light, nutrients, water, and space, which significantly lowers productivity and degrades food quality (Zimdahl, 2018). Depending on the crop type, weed species, and length of competition, yield losses from unchecked weeds in vegetables have been found to range from 30% to 70% (Knezevic *et al.*, 2017). Chemical pesticides and hand weeding have historically been the main methods used to manage weeds in vegetable crops. The development of herbicide-resistant weed biotypes, contamination of the environment, and possible health concerns to humans are just a few of the problems caused by the excessive and repetitive use of the same herbicides, despite the fact that they offer rapid and efficient weed suppression (Heap, 2023). Because selective herbicides are scarce and comparable crops are repeatedly grown in intensive production systems, vegetable cropping systems are especially susceptible to herbicide resistance (Beckie *et al.*, 2019). These issues have brought attention to the shortcomings of single-method weed control techniques and the pressing need for additional environmentally friendly methods. In order to keep weed populations below economic threshold levels, Integrated Weed Management (IWM), a comprehensive and ecologically orientated strategy, integrates various weed management techniques in a compatible way (Swanton *et al.*, 2008). The fundamental idea behind IWM is to use our understanding of weed biology and ecology to create a variety of management techniques that minimise detrimental effects on the environment while lowering weed load. Instead of relying just on chemical management for vegetable crops, IWM stresses cultural methods, mechanical and physical controls, preventive measures, and the prudent use of herbicides (Riemens *et al.*, 2022). The capacity of IWM to interfere with weed life cycles and gradually lower the soil weed seed bank accounts for its efficacy. Crop competitiveness is increased and weed emergence is suppressed through techniques like mulching, crop rotation, cover crops, and optimal planting geometry (Teasdale *et al.*, 2007). Particularly in organic and smallholder vegetable systems, mechanical and physical techniques including hand weeding, interrow cultivation, and soil solarisation can reduce weeds (Bond & Grundy, 2001). In order to prevent the development of resistance, the application of herbicides as part of IWM relies on appropriate timing, dose optimisation, and rotation of modes of action (Norsworthy *et al.*, 2012). Recent developments in digital technologies and precision agriculture have created new possibilities for increasing IWM efficiency in vegetable crops. Robotic weeders, sensor-based sprayers, and precision weed management systems allow site-specific weed control and lower herbicide inputs (Young *et al.*, 2014). Despite these developments, IWM use is still restricted in many areas because of labour shortages, knowledge gaps, and financial concerns. In order to direct researchers, extension agents, and farmers towards sustainable weed management in vegetable production systems, a thorough analysis of integrated weed management techniques is necessary.

Weed Flora and Ecology In Vegetable Crops

The degree of weed infestation and the efficacy of weed management techniques in vegetable crops are largely determined by weed flora and ecological traits. Intensive cultivation techniques, frequent irrigation, high nutrient inputs, and repeated cropping cycles are common characteristics of vegetable cropping systems, which foster the emergence and spread of a variety of weed species (Zimdahl, 2018). Therefore, creating successful integrated weed management (IWM) programs requires an understanding of weed composition, emergence behaviour, and competitive relationships.

Weed diversity and emergence patterns:

Due to ongoing soil disturbance and year-round crop production, vegetable fields typically contain a variety of annual, biennial, and perennial weeds. Fast-growing annual broadleaf weeds like *Amaranthus* spp., Chenopodium album, and Portulaca oleracea; grassy weeds like Echinochloa colona and Digitaria spp.; and troublesome perennials like Cyperus rotundus and Convolvulus arvensis are common weed groups in vegetable systems (Rao *et al.*, 2015). Crop type, planting season, soil conditions, and management techniques all affect which weed species predominate. In vegetable crops, weed emergence frequently coincides with crop establishment, creating fierce competition in the early phases of growth. Many weeds can remain in the soil seed bank for several years due to their strong capacity for seed production and extended seed dormancy (Buhler *et al.*, 2001). By preserving ideal soil moisture and temperature conditions, frequent irrigation and shallow tillage—common practices in vegetable cultivation—further promote weed germination. As a result, early-season weed flushes are a significant problem for vegetables and call for prompt management actions.

Critical period of weed competition:

Vegetable crops are especially vulnerable to early weed interference, making the idea of the critical period of weed competition (CPWC) crucial. According to Knezevic *et al.*, (2017), the CPWC is the amount of time that weeds must be controlled in order to avoid unacceptable production losses. In many vegetables such as tomato, onion, cabbage, and leafy greens, the CPWC occurs shortly after crop emergence and may extend for several weeks due to slow initial growth and limited canopy development (Hall *et al.*, 1992). Even if weeds are removed later, yield decreases may be irreparable if weeds are not controlled during this crucial time. Reduced photosynthetic efficiency and stunted crop growth result from weeds competing with crops for vital resources such light, nutrients, water, and space (Swanton *et al.*, 2010). Weed interference can negatively impact crop quality, harvest efficiency, and market value in addition to production losses. This is especially important for high-value vegetable crops.

Crop–weed interactions and seed bank dynamics:

Crop layout, growth rate, and management techniques all affect crop-weed interactions in vegetable systems. Wider row spacing or sluggish canopy closure allow more light to reach the soil's surface, which promotes the growth of weeds (Liebman *et al.*, 2001). On the other hand, strategies that increase crop competitiveness, such aggressive cultivars and optimal planting density, can inhibit weed growth by reducing the availability of resources. Management decisions have a significant impact on the soil weed seed bank, which is the main source of future weed infestations. Continuous use of identical weed management techniques, especially herbicides with similar modes of action, can change the species composition of weeds and encourage the dominance of resistant or tolerant species (Beckie *et al.*, 2019). According to Norsworthy *et al.*, (2012), integrated treatments that incorporate mechanical, chemical, and cultural techniques can minimise long-term weed pressure by gradually depleting the seed bank. The basis for successful integrated weed management in vegetable crops is an understanding of weed ecology, including emergence patterns, competitive abilities, and seed bank dynamics. The selection and timing of suitable control techniques are made possible by this ecological information, which ultimately improves weed suppression while lowering financial and environmental costs.

Principles of integrated weed management

A sustainable strategy called Integrated Weed Management (IWM) uses a variety of weed management techniques to lower weed pressure while lowering risks to the environment and the economy. Instead of depending just on one control technique, IWM integrates cultural, mechanical, biological, and chemical approaches. Reducing the introduction and spread of weeds is mostly dependent on preventive measures including crop rotation, safe seed use, and prompt field cleanliness. Crop competitiveness against weeds is increased by cultural methods such as competitive crop varieties, optimal planting density, and appropriate fertiliser and water management (Swanton & Weise, 1991). Weed populations can be decreased by mechanical techniques like tillage and hand weeding, especially in the early phases of crop growth. Chemical treatment increases the effectiveness of weed management and slows the emergence of herbicide resistance when applied sparingly and as a supplemental technique (Harker & O'Donovan, 2013).

Prevention of Weed Introduction and Spread:

The first and most economical integrated weed management principle is prevention. Its main goal is to reduce the amount of weed seeds and propagules that enter and spread across vegetable fields. Using certified weed-free seeds, properly decomposed organic manures, and sanitising farm equipment and irrigation channels are examples of preventive methods (Zimdahl, 2018). Since these regions frequently serve as reservoirs for weed seeds, it is crucial to effectively manage weeds along field boundaries, bunds and non-cropped areas. Long-term management expenses are decreased and future infestations are decreased by preventing weed seed production and distribution.

Understanding Weed Biology and Ecology:

International Weed Management requires a solid understanding of weed biology and ecology. The life cycles, emergence patterns, dormancy mechanisms, and competitive capacities of weed species vary. Growers can target weeds at their most vulnerable growth stages by being aware of these traits (Knezevic *et al.*, 2017). Early-season weed emergence in vegetable crops frequently occurs at the same time as crop establishment, thus prompt action is essential. Ecological knowledge aids in the selection of suitable control strategies and the timing of those strategies to maximise their efficacy.

Reduction of the Soil Weed Seed Bank:

The main cause of recurrent weed infestations is the soil weed seed bank. Reducing this seed bank gradually through integrated solutions is one of the fundamental tenets of IWM. Seed bank depletion is largely caused by practices such crop rotation, weed removal prior to blooming, preventing seed set, and using cover crops (Buhler *et al.*, 2001). Consistent application of these techniques eventually results in less weed pressure and a decreased need for aggressive management methods.

Table 1: Effect of mulches and cover crops on weed suppression in vegetable crops.

Practice	Weed suppression mechanism	Effectiveness	Additional benefits	Key reference
Organic mulch (straw, residues)	Light blockage, physical barrier	Moderate–High	Improves soil organic matter	Bond & Grundy (2001)
Plastic mulch (black polyethylene)	Complete light exclusion	High	Soil warming, moisture conservation	Lamont (2005)
Biodegradable mulch	Light exclusion	Moderate–High	Eco-friendly alternative	Kasirajan & Ngouajio (2012)
Cover crops (rye, clover)	Competition allelopathy	Moderate	Seed bank reduction, soil health	Teasdale *et al*., (2007)
Rolled cover crop residues	Surface mulch effect	Moderate–High	Reduced erosion	Liebman *et al*., (2001)

Integration of Multiple Weed Control Methods:

A technique relying solely on one strategy, integrated weed control emphasises the joint application of cultural, mechanical, physical, biological, and chemical techniques. When other strategies are inadequate, chemical treatments offer effective control, mechanical methods physically remove weeds, and cultural practices increase crop competitiveness (Swanton *et al*., 2008). By combining these techniques, we can increase weed suppression, improve system resilience, and reduce the likelihood of weed adaptation.

Timely Weed Control Based on Critical Period of Competition:

A fundamental tenet of IWM is timely weed control, especially for vegetable crops that are extremely vulnerable to early weed interference. According to Knezevic *et al*., (2017), weed control is crucial during the critical period of weed competition (CPWC) in order to avoid major yield losses. Better crop establishment, increased yields, and higher-quality produce are all guaranteed by effective weed control during this time.

Judicious Use of Herbicides and Resistance Management:

When applied sparingly and in conjunction with non-chemical techniques, herbicides continue to be a crucial part of IWM. To prevent the development of resistance, rational herbicide use entails choosing the right herbicides, switching up their modes of action, and using the recommended dosages (Norsworthy *et al*., 2012). In vegetable systems, where there are few herbicide alternatives and frequent use can quickly select resistant weed biotypes, managing herbicide resistance is crucial (Beckie *et al*., 2019).

Monitoring and Adaptive Management:

Successful IWM requires ongoing weed flora monitoring and management outcome assessment. Weed populations are dynamic and can change as a result of environmental factors and management strategies. The long-term sustainability and efficacy of weed control programs are ensured by adaptive management, which permits strategy modification in response to observable changes (Riemens *et al*., 2022).

Cultural weed management parctices in vegetable crops

A key element of integrated weed management (IWM) in vegetable crops is cultural weed management, which involves modifying agronomic techniques to promote crop development over weeds. By increasing crop competitiveness, interfering with weed life cycles, and decreasing opportunities for weed establishment, cultural activities reduce weeds indirectly as opposed to directly. Cultural techniques have an important preventive and complementing function in vegetable production systems, where crops are frequently vulnerable to early weed competition (Liebman *et al*., 2001).

Crop Rotation and Cropping System Diversification:

One of the best cultural techniques for controlling weeds in vegetable cropping systems is crop rotation. Weed life cycles are disrupted and the dominance of particular weed species is prevented by rotating crops with diverse growth habits, planting dates, and resource requirements (Rao *et al*., 2015). The accumulation of specific weed flora adapted to certain systems is frequently encouraged by the continuous cultivation of the same or comparable vegetable crops. Incorporating grains, legumes, or cover crops into vegetable-based rotations modifies resource availability and soil disturbance patterns, which lowers weed pressure. By altering selection pressures, diversified cropping systems also aid in the management of herbicide-resistant weeds. Crop rotation lowers dependency on a single technique and promotes long-term weed suppression by enabling the employment of various herbicides and weed control strategies (Beckie *et al*., 2019).

Planting Time, Spacing, and Crop Geometry:

A crucial cultural tactic for weed control is the manipulation of crop shape and planting time. Crops can reduce early-season competition by avoiding peak weed emergence periods by modifying the dates of sowing or transplanting (Zimdahl, 2018). For instance, crops frequently have a competitive advantage over emergent weeds when veggies are transplanted as opposed to directly seeded. According to Liebman *et al*., (2001), optimal plant spacing and row orientation reduce the amount of light available to weeds at the soil's surface by promoting canopy formation and crop light interception. It has been demonstrated that, where agronomically possible, narrow row spacing and higher plant densities inhibit weed growth in a number of vegetable crops by encouraging quick canopy closure (Teasdale *et al*., 2007).

Competitive Cultivars and Seedling Vigour:

Weed reduction in vegetable crops can be greatly enhanced by choosing competitive cultivars with quick early growth, strong root systems, and more canopy development. Crop competitiveness is receiving more attention as a weed management characteristic, even though the majority of vegetable breeding projects prioritise yield and quality traits (Swanton *et al*., 2010). Particularly during the crucial stage of weed competition, vigorous seedlings can outcompete weeds for light, nutrients, and water. Crop competitiveness is further increased by using robust, healthy transplants rather than feeble seedlings. According to Bond and Grundy (2001), seedlings cultivated in nurseries frequently have an advantage against weeds, allowing them to establish quickly and minimise weed interference during early growth phases.

Nutrient and Water Management:

Crop-weed competition in vegetable systems is significantly influenced by irrigation and nutrient management. Weeds, particularly fast-growing annual species, can benefit disproportionately from excessive or poorly timed fertiliser treatment (DiTomaso, 1995). Instead of spreading fertilisers, band placement close to crop rows can increase crop uptake while restricting weed access to nutrients.

Similarly, weed germination and growth are suppressed by precision irrigation techniques like drip irrigation, which lower soil moisture availability in inter-row intervals (Zimdahl, 2018). Vegetable crops benefit greatly from drip irrigation because it minimises favourable conditions for weed development throughout the entire field while meeting crop water requirements.

Integration with Other IWM Components:

In combined with mechanical, physical, and chemical control techniques, cultural weed management strategies work best. Cultural methods greatly lessen weed pressure and increase the efficacy of other management techniques, even though they might not be able to completely control weeds on their own (Swanton *et al*., 2008). Cultural methods lessen the need for heavy herbicide dosages or frequent mechanical operations by reducing weed density and vigour. Overall, by increasing crop competitiveness, lowering weed seed bank inputs, and reducing reliance on chemical control, cultural weed management techniques support sustainable vegetable production. For vegetable cropping systems to achieve long-term, environmentally sound weed management, their integration within IWM frameworks is crucial.

Mulches and cover crops for weed suppression

In vegetable crops, mulches and cover crops are crucial cultural elements of integrated weed management (IWM) because they improve crop competitiveness and alter the soil environment to suppress weeds. According to Teasdale *et al*., (2007), these techniques improve soil health and moisture conservation while reducing weed establishment through physical barriers, light interception, and allelopathic effects.

Mulching for Weed Management:

Mulching is extensively used in vegetable production because it works well to improve crop microclimate and suppress weeds. By obstructing sunlight and physically preventing weed seedling emergence, organic mulches including straw, crop residues, compost, and leaf litter suppress weeds (Bond & Grundy, 2001). Additionally, as these components break down, they increase microbial activity and soil organic matter. However, organic mulches may need a lot of material and can contain illnesses or pests. High-value vegetable crops including tomatoes, capsicums, cucumbers, and strawberries frequently employ plastic mulches, especially black polyethylene films. By totally blocking light from reaching the soil's surface, plastic mulches effectively restrict weed growth (Lamont, 2005). Plastic mulching also raises the warmth of the soil, lowers evaporation losses, and increases the effectiveness of nutrient utilisation. Notwithstanding these advantages, non-biodegradable plastic mulch disposal raises environmental issues. Biodegradable mulches have been the subject of recent studies as environmentally beneficial substitutes for traditional polymers. Although they are more expensive and have varied rates of breakdown, biodegradable mulches provide similar weed

Table 2: Chemical Weed Control and Herbicide Resistance Management in Vegetable Crops.

Aspect	Description	Examples / Key Points	Supporting reference
Herbicide application timing	Use of herbicides at different crop growth stages	Pre-plant, pre-emergence, and post-emergence herbicides commonly used in vegetables	Senseman (2007)
Mode of action (MOA)	Herbicides classified based on biochemical target sites	ALS inhibitors, PS II inhibitors, ACCase inhibitors, synthetic auxins	Duke (2012)
Causes of herbicide resistance	Factors leading to resistance development	Repeated use of same MOA, high selection pressure, limited herbicide options	Powles & Yu (2010)
Types of resistance	Mechanisms by which weeds survive herbicide application	Target-site resistance and non–target-site resistance	Délye *et al.*, (2013)
Herbicide rotation	Alternating herbicides with different MOAs	Reduces selection pressure on weed populations	Norsworthy *et al.*, (2012)
Herbicide mixtures	Use of tank-mixed or sequential herbicides	Improves control spectrum and delays resistance	Beckie & Reboud (2009)
Dose and application accuracy	Importance of recommended dose and timing	Sub-lethal doses accelerate resistance evolution	Neve *et al*., (2009)
Integration with non-chemical methods	Combining herbicides with cultural & mechanical practices	Crop rotation, mulching, mechanical weeding	Mortensen *et al*., (2012)
Impact on vegetable production	Consequences of resistance development	Yield loss, increased production cost, limited options	Heap (2023)
Resistance management strategies	Long-term solutions under IWM	MOA rotation, monitoring, diversified weed control	Beckie *et al*., (2019)

suppression while lowering plastic pollution (Kasirajan & Ngouajio, 2012).

Cover Crops and Living Mulches:

In vegetable-based cropping systems, cover crops significantly reduce weed growth by emitting allelopathic substances and competing for resources. Cereals (rye, oats), legumes (clover, vetch), and brassicas (mustard) are common cover crops used for weed control; each has unique benefits (Teasdale *et al*., 2007). Weed germination and growth are inhibited by dense cover crop canopies because they lower light availability at the soil's surface. By lowering the replenishment of weed seed banks, cover crops also aid in long-term weed control. Cover crop leftovers provide long-term weed suppression during succeeding vegetable cropping seasons when they are left on the soil's surface as mulch (Liebman *et al*., 2001). In conservation and organic vegetable systems, the use of rolled or crimped cover crops to provide surface mulch layers that reduce weed growth is growing. Weed reduction can be further improved by cultivating low-growing plant species alongside vegetables in living mulches. To prevent yield penalties, however, the rivalry between the vegetable crop and the live mulch for water and nutrients must be carefully controlled (Hartwig & Ammon, 2002).

Integration within IWM Framework:

When combined with other IWM elements like crop rotation, mechanical weeding, and the use of selective herbicides, mulches and cover crops are most successful. According to Swanton *et al*., (2008), these methods greatly lessen weed pressure and the need for chemical pesticides, even though they might not be sufficient on their own. In vegetable cropping systems, mulches and cover crops are therefore environmentally friendly and sustainable methods of suppressing weeds.

Mechanical and Physical weed control methods

In vegetable crops, mechanical and physical weed control techniques are essential parts of integrated weed management (IWM), especially in production systems where chemical weed control is restricted, limited, or unwanted. These techniques, which include uprooting, cutting, burial, and exposure to deadly temperatures, reduce weeds by direct physical action. Mechanical and physical approaches offer dependable and environmentally safe options in vegetable cropping systems, where crops are frequently sensitive to herbicide damage and need weed-free environments during early growth phases (Tillett *et al*., 2008).

Mechanical weed control Methods:

Manual weeding, hoeing, interrow cultivation, and mechanical tillage are examples of mechanical weed management. Hand weeding, which is particularly crucial in smallholder farming systems and transplanted vegetables, is still one of the most accurate weed control techniques. It enables the selective eradication of weeds without endangering crops or soil health, but being labour-intensive (Gianessi & Reigner, 2007). For row-grown vegetables including cabbage, tomatoes, onions, and cauliflower, interrow cultivation with mechanical weeders is frequently used. By uprooting immature weeds, disturbing the earth's surface, and improving soil aeration, these tools promote crop growth (Griepentrog & Dedousis, 2010). Timing and soil conditions have a big impact on how well mechanical weed control works. Early seedling stages, when root systems are thin and easily removed, are when weeds are most vulnerable. Crop damage may rise and weed control may be only partially achieved if mechanical operations are delayed (Rasmussen *et al.*, 2012). However, by revealing buried seeds, repeated soil disturbance may encourage more weed emergence, highlighting the necessity of integration with other IWM techniques.

Physical Weed Control Methods:

The methods of solarisation, scorching, steaming, hot-water treatment, and electrocution are examples of physical weed control techniques. In order to capture sun energy and raise soil temperatures to levels that are fatal to weed seeds and propagules, soil solarisation entails covering moist soil with transparent polyethylene sheets. In protected cultivation systems and vegetable nurseries, this technique has proven effective, especially in warm regions (Stapleton & DeVay, 1986). By rupturing plant cell membranes with controlled heat, flame weeding causes weeds to dry up quickly. It is frequently used in organic vegetable production and works well against tiny broadleaf weeds (Rifai *et al.*, 2002).

Advanced Physical Weed Control Methods:

Emerging physical weed management approaches that effectively reduce weeds without leaving behind chemical residues include steaming and applying hot foam. Although their high energy requirements and operating costs now prevent widespread implementation, these techniques are especially helpful in high-value vegetable crops and greenhouse systems (Peruzzi *et al.*, 2017). Another cutting-edge method being developed for targeted and residue-free weed management is electrical weed control, which uses high-voltage currents to damage weed tissues (Vigneault *et al.*, 2009). The accuracy and effectiveness of mechanical weed management have been greatly enhanced by recent technology developments. Intelligent weeding machines and automated camera-guided cultivators can differentiate between crops and weeds while causing the least amount of crop harm (Lati *et al.*, 2016). These technologies are especially useful for intensive vegetable production systems since they decrease reliance on labour and increase the precision of weed management.

Chemical weed control and herbicide resistance management

Chemical weed control is still a crucial part of integrated weed management (IWM) for vegetable crops because of its quick action, dependability, and efficiency in managing a variety of weed species. Because vegetable production systems frequently have high crop value, short growing seasons, and strict weed-free criteria, chemical management is a desirable alternative for farmers. However, an over-reliance on herbicides has resulted in a number of problems, such as environmental contamination, herbicide resistance, and worries about food safety, making the use of chemical weed management techniques more prudent and comprehensive (Duke, 2012).

Role of Herbicides in Vegetable Crops:

In vegetable crops, herbicides are frequently used to control weeds during crucial growth stages when competition can result in significant output losses. Depending on the type of crop, weed flora, and cropping system, pre-plant, pre-emergence, and post-emergence herbicides are used. Although selective herbicides are recommended to reduce crop damage, they are less readily available for vegetables than for field crops (Senseman, 2007). Because of this, farmers frequently use a limited variety of herbicides, which raises the possibility of resistance emerging. In the early stages of crop establishment, when mechanical or manual weeding may be challenging or unsuccessful, chemical weed management is very helpful. Pre-emergence herbicides can inhibit early-season weeds in transplanted vegetables, minimising the requirement for numerous manual interventions (Ross & Lembi, 2009). Chemical treatment is not enough for long-term weed control, despite these advantages.

Herbicide Resistance: Causes and Current Status:

Globally, herbicide resistance has become a serious challenge to sustainable vegetable production. When weed populations develop the capacity to withstand doses of herbicides that would typically be fatal, this is known as herbicide resistance. The main cause of resistance evolution is the repeated application of herbicides with the same mechanism of action, frequently at high frequency (Powles & Yu, 2010). Because of their intensive cultivation and low diversity of herbicides, vegetable cropping systems are especially sensitive. Herbicide resistance management is an essential part of

IWM and calls for a proactive, multifaceted strategy. Rotating herbicides with various modes of action is one of the best ways to lessen selection pressure on weed populations (Norsworthy *et al*., 2012). When applied correctly, tank mixing or the sequential spraying of herbicides with different modes of action might further postpone the development of resistance. It is equally vital to use the recommended dosages of herbicides and to apply them at the right times. Partially resistant individuals may be able to survive and procreate at sub-lethal dosages, hastening the evolution of resistance (Neve *et al*., 2009). As a result, following label guidelines and using exact application methods is crucial.

Strategies for Herbicide Resistance Management:

A proactive, multifaceted strategy is needed to manage herbicide resistance, which is an essential part of IWM. Rotating herbicides with various modes of action is one of the best ways to lessen the selection pressure on weed populations (Norsworthy *et al*., 2012). When applied correctly, tank mixing or the sequential spraying of herbicides with several modes of action can further postpone the emergence of resistance. Applying herbicides at the right times and using the recommended dosages are equally crucial. Partially resistant individuals may be able to survive and procreate in sub-lethal doses, hastening the evolution of resistance (Neve *et al*., 2009). As a result, following label guidelines and using accurate application methods is crucial.

Integration of Chemical and Non-Chemical Methods:

Herbicides should be utilised as supplementary tools rather than as stand-alone remedies, according to integrated weed management. Weed density and the need for herbicides are decreased when chemical management is combined with cultural techniques such crop rotation, mulching, and competitive crop stands (Mortensen *et al*., 2012). The development of resistant biotypes can be restricted by using mechanical and physical techniques to manage runaway weeds and stop seed production. Strategic distribution of herbicides, such as banded application over crop rows, which lowers overall herbicide input while preserving efficient weed control, is another aspect of herbicide use under IWM frameworks (Senseman, 2007). By more precisely targeting weeds and reducing off-target effects, precision application technologies significantly improve the effectiveness of chemical weed management.

Environmental and Safety Considerations:

Environmental weed control in vegetable crops raises serious concerns about food quality and environmental safety. Overuse or incorrect application of herbicides can result in residue buildup on produce, non-target plant damage, and contamination of soil and water (Duke, 2012). In order to mitigate these dangers, IWM encourages responsible herbicide stewardship through lower dosages, fewer applications, and integration with non-chemical techniques. All things considered, chemical weed control is still a crucial but strictly controlled part of integrated weed management in vegetable crops. Herbicides can effectively contribute to sustainable weed management while reducing resistance development and environmental effects when used sparingly and in conjunction with mechanical and ecological tactics.

Emerging and precision weed management approaches

Due to their ability to increase weed control effectiveness while lowering environmental effects, emerging and precision weed management techniques have grown in significance in contemporary vegetable production systems. Precision weed management minimises excessive pesticide use and labour needs by focussing on the timely and site-specific delivery of control measures, in contrast to traditional uniform weed management techniques. By improving the accuracy and efficacy of mechanical, chemical, and cultural control techniques, these strategies support Integrated Weed Management (IWM) (Gebbers & Adamchuk, 2010). Accurate weed population mapping and identification are made possible by recent technological advancements like GPS, GIS, remote sensing, and sensor-based systems, which enable targeted interventions only where weeds are present (Christensen *et al*., 2009). Additionally, crop-weed discrimination and automated weed management have been enhanced by the combination of robots, machine vision, and decision support systems, especially in high-value vegetable crops (Slaughter *et al*., 2008; Fennimore *et al*., 2016). Precision weed management has great potential for effective and sustainable weed control in vegetable cropping systems, despite obstacles relating to cost and technical complexity.

Precision Weed Management and Weed Mapping:

New and precision-based weed management strategies have emerged as a result of recent developments in agricultural technology, providing new possibilities for long-term weed control in vegetable cropping systems. These methods seek to lower labour costs, herbicide inputs, and environmental effects while increasing the precision, effectiveness, and selectivity of weed management techniques. Precision weed control is a supplementary tactic in integrated weed management

(IWM) that improves the efficacy of conventional cultural, mechanical, and chemical approaches (Gebbers & Adamchuk, 2010). The geographical and temporal diversity of weed populations within a field is the foundation of precision weed management. Precision methods target weeds only where and when they appear, in contrast to traditional uniform weed management techniques. Weed distribution in vegetable fields may be precisely mapped thanks to technologies like remote sensing, geographic information systems (GIS), and global positioning systems (GPS) (Christensen *et al*., 2009). By identifying weed hotspots and implementing site-specific control strategies, weed maps assist farmers in cutting down on needless inputs.

Sensor and Machine Vision Systems:

Precision weed detection has greatly improved thanks to machine vision and sensor-based technology. Selective mechanical or chemical weed control is made possible by camera-guided devices that can differentiate between crops and weeds based on shape, colour, and spectral properties (Slaughter *et al*., 2008). For crops cultivated in rows, where precise inter-row and intra-row weed control is essential, these systems are very helpful. Herbicide use can be significantly reduced without sacrificing the effectiveness of weed management with sensor-based sprayers that only apply herbicides when weeds are identified (Biller, 1998).

Robotic, AI and Decision Support Tools:

One of the most promising developments in vegetable weed control is robotic weed control. Artificial intelligence (AI), machine learning algorithms, and precision tools enable autonomous robots to recognise and eliminate weeds using mechanical, thermal, or targeted chemical techniques (Fennimore *et al*., 2016). These technologies are ideal for high-value vegetable crops and organic production systems since they lessen reliance on manual labour and herbicides. However, widespread adoption is still hampered by high initial investment costs and restricted availability. Digital platforms and decision support systems (DSS) are becoming increasingly important in precise weed management. To suggest the best weed control methods, DSS incorporates information on weed biology, weather, soil characteristics, and crop growth (Rydahl *et al*., 2020). These technologies increase productivity and lower hazards by assisting farmers in making well-informed decisions about the time and choice of weed management techniques.

Challenges and Future Prospects:

Emerging and precise weed management techniques have a number of drawbacks despite their potential advantages, including as high costs, restricted accessibility for smallholder farmers, and technical complexity. Furthermore, precise weed identification in intricate vegetable canopies is still a technological issue (Peteinatos *et al*., 2020). However, it is anticipated that acceptance and integration of precision tools within IWM frameworks would increase with further research, technological advancement, and legislative support. All things considered, new technologies hold great potential for enhancing the resilience, sustainability, and effectiveness of weed control in vegetable cropping systems.

Conclusion

A viable and sustainable solution to the intricate weed issues connected to intensive vegetable production systems is integrated weed management. Due to the variety of vegetable crops, their susceptibility to early weed competition, and the scarcity of specific herbicides, relying solely on one weed control technique is dangerous and ineffective over time. A balanced framework for efficient weed suppression while reducing environmental and financial costs is provided by the integration of cultural, mechanical, physical, chemical, and developing technological techniques. Understanding weed ecology and implementing control techniques at the appropriate time and scale are critical to the success of integrated weed management in vegetable crops. Crop rotation, competing crop stands, mulching, mechanical weeding, prudent pesticide use, and preventive measures all work together to lessen weed pressure and soil weed seed bank depletion. These varied approaches increase system resilience against herbicide resistance and climate unpredictability in addition to improving weed control effectiveness. New opportunities to improve integrated weed management tactics are presented by emerging digital and precision technology. Particularly in high-value vegetable crops, technologies like robotic weeders, sensor-based weed detection, and decision support systems offer the potential to minimise labour dependency and maximise input use. However, high initial costs, technical complexity, and restricted access for smallholder farmers continue to impede the widespread implementation of these advances. The development of affordable, user-friendly technologies and their adaptation to various agro-ecological settings should be the main goals of future research. Strong extension networks, farmer education, and policy backing are necessary for integrated weed management to be implemented successfully. Farmers' awareness and adoption of ecological weed control, resistance management, and safe pesticide use can all be enhanced by capacity-building initiatives. To assess the combined effects of various weed management techniques on weed dynamics, crop yield, soil health, and farm profitability, long-term field studies are also necessary. Overall, by lowering reliance on chemical herbicides, preserving natural resources, and guaranteeing long-term weed control, integrated weed management provides a workable route towards sustainable vegetable production. To fully realise the potential of integrated weed management in vegetable cropping systems, researchers, extension specialists, legislators, and farmers must continue their research, innovate, and work together.

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