Review Article

Advancing Integrated Weed Management Strategies in Sustainable Agriculture: Synergizing Cultural, Mechanical, Biological, and Precision Farming Approaches for Effective Weed Control and Environmental Stewardship

Abstract

A systematic approach to weed management, integrated weed management combines various weed control techniques to give the crop an advantage over weeds. Developing more sustainable agricultural systems is hampered primarily by weeds. In order to feed the world's population and preserve the ecosystems and biodiversity that we depend on, agriculture must employ sustainable weed management techniques. Integrated weed management strategies that incorporate various tools and techniques represent progress; however, a significant number of these strategies continue to rely excessively on a limited number of tools. The multiple approach integrated weed management can be fulfilled by incorporating any suitable physical, biological, or chemical weed management strategy into the current conservation agriculture weed management practice. A extensive body of research is used to support a balanced discussion of the benefits and drawbacks of traditional weed management strategies, which include cultural, biological, chemical, and manual controls. The framework comprises five key pillars: Diverse cropping systems, the selection and establishment of cultivars, field and soil management, direct control, and monitoring and evaluation of the cross-cutting pillar. IWM needs to transform from a descriptive science to a predictive science in the future. In this paper, we examine the most popular traditional and unconventional methods of controlling weeds from a sustainability standpoint, emphasizing the use of automated and precision weed control technologies related to precision weed management. Furthermore, the review assesses the environmental implications and social effects of conventional and non- conventional weed management strategies.

Keywords : IWM, Sustainable agriculture, weed control technologies.

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Introduction-

Sustainable weed management (SWM), which is predicated on the application of multiple weed strategies, encompasses a range of weed management strategies, including integrated weed management (IWM). Integrated weed management aims to increase grower profit and maximize crop productivity through the coordinated application of preventive strategies, scientific knowledge, management skills, monitoring procedures, and the efficient use of control practices Antonio et al.,2020 . It has long been suggested that the application of suitable mechanical, chemical, biological, and cultural weed control techniques can result in the suitable and efficient management of weeds young *et al*.,2017 . This approach is known as integrated weed management or IWM.

By lowering conventional agriculture's reliance on outside inputs, integrated weed management could offer a more sustainable method of producing crops McErlich *et al.*,2013. Studies have suggested integrated weed management (IWM) strategies that integrate chemical, mechanical, biological and physical methods with weed prevention measures (*e.g.*, managing the seed bank and enhancing crop competitiveness) to decrease the application of chemical herbicides Gao *et al.*,2024. Herbicide resistance and cross-resistance are two issues that arise from the occasional disregard for the responsible use of herbicides. Its becoming more and more obvious that using herbicides alone to control weeds is not a long-term, viable or efficient approach Nath *et al.*,2024. In response to customer demand, farmers are converting from conventional agriculture, which heavily relies on chemicals, to more environmentally friendly and sustainable farming methods. The introduction of more environmentally friendly and sustainable weed control options is the result of this evolution.

Preventing weeds from spreading instead of controlling them after they have grown and become harmful is the core principle of sustainable weed management Hasan *et al.*,2015. Global agricultural productivity is being threatened by weeds developing resistance to herbicides. Improved crop productivity and weed control need the use of sustainable an d environmentally friendly methods Kumam *et al.*,2023. There is a need for better management of the worlds agricultural resources while avoiding the negative environmental effects due to the growing global population and the ensuring requirement to assure food supply by boosting agricultural production. For this reason, maintaining weed control in the agricultural system is crucial for the survival of humankind both now and in the future.

Enhancing sustainability and agricultural productivity can benefit from the development of precision technologies that are inherent in weed control, in addition to integrated management Radicetti *et al.*,2021. Numerous new developments in sustainable weed management techniques, strategies, and knowledge are covered in this special issue. It also became clear that using a variety of techniques together frequently improves the ability to suppress weeds Restuccia *et al.*,2023 . Herbicide use, crop rotation, and the use of cover crops have all enhanced biomass output and crop yield while lowering weed density, demonstrating the need of integrated weed control for production system Rudell *et al.*,2023 .
IWM, however, need to focus more on general technique diversity than on singling out one approach over another. Repeatedly using any weed management techniques puts a lot of pressure on weeds to adapt and become resistant to it Harker *et al.*,2013.

2. Weeds: Threat or Benefit?

For as long as agriculture has been, there have been weeds, and farmers have known that the presence of those unsown plant species inhibits crop development from the very beginning they were trying to grow intended to produce Radicetti *et al.*,2021. Moreover, weeds represent the most expensive class of agricultural hazards, accounting for over 45% of field crop yield losses, when compared to crop disease (25%) and insect pests (20%) Scavo *et al.*,2020. Weed- related to yield losses depend upon various factors, including the time of weed emergence, weed density, type on weeds and crops, etc. Unmanaged weeds can cause a yield loss of 100% Peerzada *et al.*,2019. Furthermore, weeds engage in interactions with other biological agents of the ecosystem, serving as a host for insects and

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pathogens which include fungi and bacteria and can seriously harm crop plants kumar *et al.*,2021. Weeds also affect water management (*e.g.*, increased losses through evapotranspiration, decreased water flow in irrigation ditches, *etc*) and lower the value of land, particularly perennial and parasitic weeds Agrawal *et al.*,2013 . In general, agricultural practices that promote biodiversity and ecosystem functioning offer, potential benefits for sustaining agricultural improved ecosystem functioning. Weeds have existed for at least as long as agriculture, and from the beginning, farmers recognized that the presence of those unsown plant species hindered the growth of the crop they were trying to grow intended to producelly offer the following benefits to the rural population: (a) increased resilence; (b) reduced reliance on pesticides; (c) more consistent incomes and (d) better quality of life Maclaren *et al.*,2020.

3. Integrated weed management

IWM is described by Buchanan 1977 as the application of various technologies in a way that is mutually beneficial. It involves the thoughtful selection, assimilation and application of effective weed control techniques while giving appropriate consideration measures with due consideration of sociological, ecological and economic implications.

Walker and Buchanan 1982 state that since the early 1970s weed scientists have accepted and regularly used the term 'IWM'. They add that some people believe IWM is just another word for weed control. Without a doubt, IWM is more descriptive and encompasses a wider range of ideas than weed control. Weed control is linked to the broader goal of ecosystem management by IWM, which emphasizes the integration of control strategies with all other practices that impact the ecosystem.

Schreiber *et al.*,1982, as a component of an effective IWM program, for instance, promoted the creation and application of mathematical models.

At least some definitions if IPM that are used today seem to be compatible with this definition Thill *et al.*,1991. In this study, we define IWM as the combination of sociologically acceptable, ecologically safe and efficacious weed control strategies to minimize weed interference below the economic injury level. Since 1981, there has been a significant advancement in a few IWM sectors.

A model for a comparatively simple monoculture cropping system model is the one created by the bioeconomic modeling effort to stimulate weed control strategies for continuous corn (*Zea mays* L.) King *et al.*,1986.

Auld et al., 1987 A recent work on the economics weed control, offers models for both short and long-term economic analysis of weed thresholds. These kinds of models can serve as a good starting point for creating effective IWM initiatives. In order to construct models for various weed species in a cropping system and to validate many of the current models, more research is required. Additionally, farmers need to receive and utilize more number of computer-based IWM decision models.

According toAltieri and Liebman 1988, the intensive use of herbicides in weed management in developed countries agroecosystems over the past few decades has led some researchers to question whether we have created herbicide treadmills similar to those developed with the intense use of insecticides.

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However, a review of that work will, however, been to reveal the massive amount of collaborative and coordinated research needed to create systems model for even an apparently straight forward IWM program. In order to create completely integrated IWM models, specialists in a number of fields will be needed, including soil science, ecology, computer science, economics, systems science, weed science, mathematics and plant pathology. Lotz *et al*.,1990 model on weed competition and yield losses in winter what is another example.

Roush *et al.*,1990 contend that rather than focusing primarily on short-term herbicides-based solutions, scientists should reassess and refocus their weed research programs in order to develop long-term weed management alternatives based on a holistic and integrated understanding of cropping systems.

Table 1: List of recent literature reviews

Article Number	Contribution of the Article	References
Article 1	Exploring the application of artificial intelligence in weed management, focusing on weed recognization and deep learning.	Vasileiou et al.,2024
Article 2	Outline the traditional and non-traditional weed control strategies from a sustainability perspective, including valuable applying precision weed control strategies.	Monteiro et al.,2022
Article 3	Summarizes the four steps involved in creating an integrated weed control strategies.	Scavo et al.,2020
Article 4	Provide an overview of the advanced technology used for precise weed removal	Rai et al.,2023
Article 5	Examine the use of AI methods for effective and sustainable weed control strategies.	Ghatrehsamani et al. 2023

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4. Redesigning weed control tactics is necessary

A Fundamentally different approach to managing weeds in cropping systems is necessary for true IWM, although redesign has not gotten as much attention as it should. Our new framework aims to help weed management move away from substitution and efficiency and toward redesign. We disagree with ‘zero tolerance policy’ or ‘take no prisoners’ approaches. Reducing weeds detrimental effects while preserving some of their ecological benefits should be the rather than their total eradication; these two objectives may even be mutually beneficial Pretty., 2018. Broadening the available ecological niche to allow for a

more diverse weed community will help prevent excessive reproduction of the same weed species or groups of weed species (*e.g.*, monocots or perennial species) in the cropping system. MacLaren *et al*.,2020 predict that a weed community with greater functional diversity will be less able to complete in any given crop.

This strategy is more "proactive" than the "reactive" strategy, which focuses on controlling weed species that have grown to be dominant and problematic. The majority of weed species have a high degree of phenotypic plasticity, which allows them to adapt to ongoing management strategy and avoid measures intended to eradicate them, such as artificial seedbeds, varying sowing dates, and mechanical weeding techniques. In response to herbicide applications, it has been repeatedly shown that weed populations adapt. It is possible that weeds can also adapt to mechanical and cultural processes, even though very few studies have shown this Owen., 2016.

Since the causal relationships are so complex throughout the weed life cycle, it is likely that there is a lack of evidence Darmency., 2019. A varied management approach that "keeps the weeds guessing" is required due to this adaptability. A five-pillared framework for designing IWM is being reviewed, and any available tools must be utilized in order to implement this strategy.

5.Five pillars for weed management

In contrast to managing of most insect pests and diseases, managing weed communities requires long term strategies. Furthermore, an advanced integrated weed management (IWM) strategy ought to influence the population dynamics of weeds at various phases of their life cycle by preventing weed establishment from seeds, rhizomes or tubers; minimizing the detrimental effects of emerging weeds on crops and reducing the replenishment of the seeds of vegetative bud bank Benaragama *et al*.,2024.
According to Riemens *et al*.,2022, our framework is predicted on the idea that various strategies affecting various life cycle stages must be combined. Farmer's strategies can be categorized into one of the following five pillars in addition to talking into one of the following five pillars in addition to taking into account the life cycle of weeds:

1. Various cropping system
2. Establishment and selection of cultivars
3. Management of field and soil
4. Direct control
5. Monitoring and evaluation

5.1 Pillar 1-

5.1.1 Diverse cropping system- The presence of diversified weed communities can support the provision of agroeco system services like pollen and nectar supply for wild bees, alternative food sources for beneficial insects and soil cover to reduce erosion, in addition to the enhanced weed control capacity of diversified cropping systems and the decreased competition with the crop Moreau *et al*.,2020 .

5.1.2 Diversification in time- Although yield reduction has rarely been reported in field studies, a review Sharma *et a*l.,2021 revealed that in laboratory experiments, the most

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susceptible times for the subsequent cash crop are during germination and the early stages of crop growth.

5.1.3 Diversification in space - For weed control and to prevent soil erosion, living ,mulches are being used in orchards and vineyards. In order to avoid the living mulch and the crop competing with one another for water during the dry season, care must be taken to regulate the biomass of the living mulch in these systems, particularly in the dry Mediterranean region Cordeau et al., 2022.

5.2 Pillar 2 -

5.2.1 Cultivar choice and crop establishment- There is some evidence that weeds in barley cultivar mixtures have less functional richness, which supports the idea of combining cultivars with contrasting phenotypes to limit the functional space available for weeds Travlos *et al.*,2023 .

5.3 Pillar 3 -

5.3.1 Field and soil management- Commonly, non-selective herbicides are used to kill emerging seedlings. However, if the goal is to reduce the use of herbicides, other methods such as superficial cultivation or non mechanical tools (like flame weeding) can also be used to control emerging weed seedling and prevent new flushes of germination and emergence Pannacci *et al*.,2017 .

5.4 Pillar 4-

5.4.1 Direct control- Controlling harvest weed seeds reduces their return to the soil seed bank, but crop yield is not negatively impacted cutting seed heads that grow above the crop canopy can also be a useful technique Akhter *et al*.,2023.

5.5 Pillar 5-

5.5.1 Monitoring and evaluation- To assess the relative effectiveness of weed management strategies over time at the field or farm level, one significant advancement would be to devise methods for methodically gathering data on weed abundance and distribution Freckleton *et al*.,2018 .

6. Weed Management and the Need for a new paradigm

Farmers have always prioritized controlling weeds since the beginning of time loddo *et al.*,2021. As a matter of fact, almost one third of the entire cost of the producing field crops goes towards weed management Boinot *et al*.,2024. Currently, there are two separate directions that corresspond to different approaches for managing weeds in agricultural systems. Weed control is mostly achieved through mechanical, cultural, and physical means, although synthetic herbicides are also widely used Abbas *et al*.,2018 . In fact, modern agriculture needs a new weed management paradigm based on ecological principles and unconventional weed management techniques Monteiro *et al*.,2022 . The integration of several weed control techniques (agronomic, mechanical, physical and chemical) within a system, instead of depending just on one method [23] Gao *et al*.,2024,

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is necessary in IWM . The purpose of this startegy for reducing the selection pressure that leads to the emergence of resistence to any one weed control technique Chauhan., 2020. Within the broader framework of IWM, emerging technologies hold the potential to transform way we currently handle weed control, while greatly reducing environment impact, like herbicide resistance or drift, as well as the high cost of inputs and labor, without compromising the effectiveness of weed control. Different approaches are being developed to monitor and identify weeds so that management actions can be implemented anytime and anywhere they are required. This paradigm shift is result of interdisciplinary effort to control weeds by utilizing powerful technology tools Korres *et al*.,2019.

6.1 Conventional weed control strategies

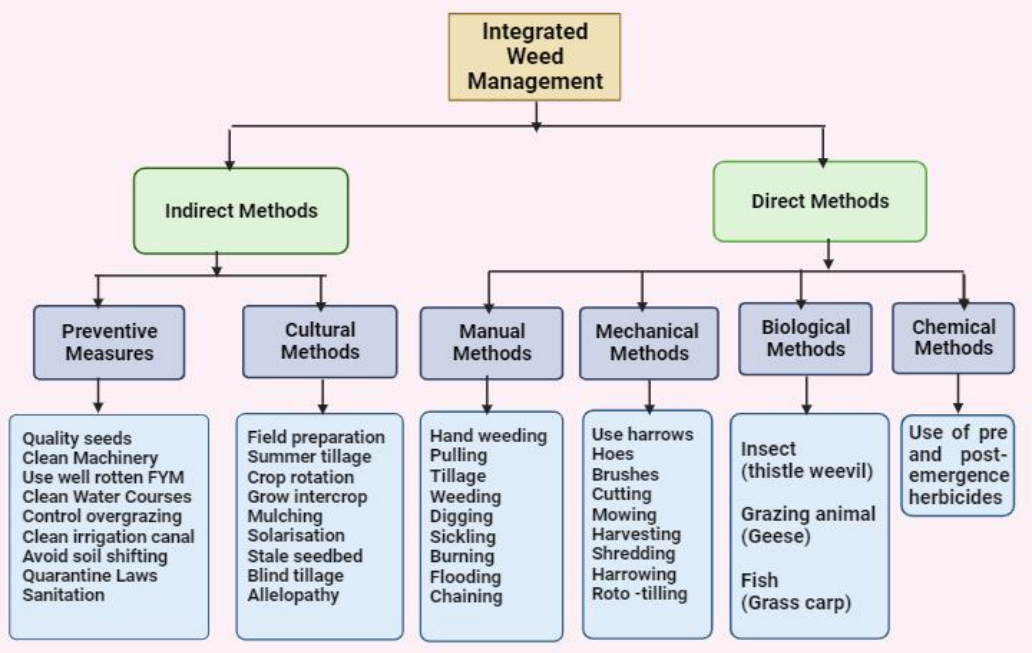

Fig 1. Conventional weed control strategies

6.1.1 Herbicide control- The most popular method of controlling weeds is the application of chemical substances, commonly refereed to as herbicide. Herbicide can improve production system with less tillage and increase production efficiency Davis *et al*.,2017and need less cost and labor. Herbicide use should be a low impact effective as possible to reduce adverse effects on the environment and move agriculture toward sustainable practicesLykogianni *et al*.,2021.

6.1.2 Mechanical control- To achieve weed control levels that are economicially acceptable, mechanical weed control is difficult and requires a combination of cultivation strategies and wedding techniques Saleh *et al*.,2024. By using physical methods, mechanical weed control destroys weeds and reduces their capacity to compete Andreasen *et al*.,2024.

6.2 Non-Conventional weed control strategies

Mulching is the process of covering the soil with plant residues, wastes, or synthetic materials. Mulching is a popular management technique that can reduce weed problems by either completely stopping weed seed germination or obstructing the growth of emerging seedlings Mennan *et a*l., 2020. Additionally, it supports biodiversity and the sustainable management of water He *et al.*,2024.

6.2.1 Cover crops and living mulches - The sustainability of farms can be increased by implementing a cover crops strategy. Any living ground cover planted in or following a primary crop that is typically removed before the next crop is planted is known as a cover crop McAmis *et al*.,2024. Cover crops increase microbial, vegetal and animal biodiversity, improve soil quality and carbon sequestration and make machinery passage easier Failla *et al.*,2021.

6.2.2 Soil solarization - An economical and environmentally beneficial method of soil disinfestration is called soil solarization Dai *et al*.,2016 , suitable with integrated crop management systems and organic farming Peerzada *et al*.,2018, that suppresses weeds by harnessing the heat of the sun Fennimore *et al*.,2016. The goal of this technique is to raise the temperature of the soil by capturing solar radiation and covering the soil with a covering, like a piece of clear or black plastic Radicetti *et al*.,2013 .

6.2.3 Thermal weed control - In order to quickly eradicate weeds without leaving chemical residues in the soil or water, thermal control methods include fire, flaming, hot water, steam, and freezing. Furthermore, unlike cultivation techniques, which bring buried seeds to the surface of the soil, thermal methods are selective for weeds and do not disturb the soil Kanellou *et al.*,2023

6.2.4 Weed control through livestock grazing - Farmers are beginning to see grazing sheep as a more practical alternative to chemicals, tillage, or moving when it comes to controlling weeds and cover crops. When grazing sheep, it’s important to take into account the necessity of temporary fencing, frequent rotations and predator protection. In addition, it is imperative for vineyard managers, for example, that sheep not be allowed to consume the crop itself Grandin., 2022.

7. Traditional weed management strategies

7.1 Manual weed control - One of the earliest methods of controlling weeds is manual control, which dates back to the early days of agriculture. The benefits of manual control are that it is easy to use, doesn’t require harm the environment or public health. For perennial weeds, it can be very effective because it can damage their underground structures Abbas *et al.*,2018.

7.2 Cultural weed control - Managing weeds within the farming system with cultural control minimizes the need for outside inputs, which is its main benefits. By strengthening the resilience of the soil and varying the sources of income, it can also increase overall farm productivity Bloomer *et al*.,2024.

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7.3 Biological weed control - There are restrictions on biological control. Results usually take time to manifest, and its efficacy might not always be 100% guaranteed. Its also possible for the control agent to become invasive itself, and there are risks of non-target effects Petit *et al*.,2018.

7.4 Chemical weed control- Herbicides are used in chemical weed control to eradicate or suppress weed growth. Herbicides can be categorized according to their selectivity, application schedule, or mode of action Sapkota *et al*.,2023.

8. Emerging technologies in weed management

8.1 Precision agriculture - Site-specific weed management (SSWM), in which weed populations are mapped within fields and herbicides are only applied where necessary, is one aspect of precision agriculture's potential role in weed management Gerhards *et al*.,2022. Herbicide use can be drastically decreased as a result, lowering expenses and negative effects on the environment. Research has demonstrated that precision agriculture works well for controlling weeds. An effective application of SSWM led to a70% decrease in the use of herbicides while maintaining equivalent yields.

8.1.1 Genomic approaches - *Amaranthus palmeri* is a weed species that has been successfully managed through the use of genomics. Its genome has been sequenced, and the genes causing herbicide resistance have been found which may make it possible to create more control strategies Borgato *et al*.,2024.

8.1.2 Robotic weed control - An important development in the field of weed management is robotic weed control. These systems make use of precision application, machine vision, and artificial intelligence (AI). Tools for weed detection and weed removal Wu *et al.*,2020

9. Environmental and Socioeconomic implications of weed management

9.1 Environmental impacts - Weed management strategies, both old and new, have an impact on the environment. Manual weeding is a common traditional method that requires a lot of labor but is generally environmentally begin because it doesn't use chemicals Weisberger *et al*.,2024.

9.2 Socioeconomic impacts- Weed management also involves expenses, such as labor costs for hand weeding or costs associated with new technologies and herbicides. The labor requirements and effects on rural livelihoods are related to the social aspects of weed management. For instance, in many developing nations, manual weeding is a major source of employment in rural areas, especially for women Das *et al.*,2024.

10.Conclusion

The implementation of integrated weed management (IWM) strategies is being a crucial step achieving to sustainable agriculture. By integration diverse control tactics like cultural, mechanical, biological, chemical methods, IWM holistic approach to weed control which minimize reliance to synthetic herbicides while preserving the environment integrity and promote long-term agriculture productivities. Throughout this comprehensive review, it had become evidence that IWM holds significant promising for sustain agriculture. By diversify weed management tactics, farmers reduced risks of herbicides resistance, minimize environmental contamination, and enhancement of soils health and biodiversity.

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Adoption of IWM practices were shown lead to long-term benefits, including improvements in crop yields, reduces production costs, and increase resilience to changing environmental conditions. Aside, the transition from the conventional weed management practices to integrated approaches may requiring changes in mindset, cultural practices as well as institution supports. Therefore, integrated weed management holds great promise for sustainable agriculture by offering innovating solutions to weed control that prioritize environmentally stewardship, economic viability and agriculture resilience. Embracing principles of integration, diversity and collaboration will be keys to realizing the full potential of IWM ensuring more sustainable futures for agriculture.

List of abbrevations

- *et al*- et alia (used to indicate 'and others' in citations)
- e.g.- exempli gratia (used to give examples)
- etc. - et cetera (used to indicate "and other things")
- IWM- Integrated weed management
- SSWM- Site specific weed management
- AI- Artificial intellegence

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