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Review Article

Sustainable Weed Management Under Climate Change: Ecological Strategies, Adaptive Mechanisms, and Future Challenges

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Abstract

Ecological weed management offers a sustainable alternative to conventional weed control by emphasizing prevention, diversification, and ecosystem-based suppression rather than reliance on single, curative interventions. This review systematically synthesizes evidence from peer-reviewed literature to evaluate ecological weed management strategies and their underlying ecological mechanisms. The literature shows that these practices suppress weed emergence and growth by reducing resource availability, disrupting weed life cycles, enhancing crop competitiveness, and lowering weed seedbank replenishment. A structured literature review approach was applied, drawing on studies retrieved from major academic databases, although the search was primarily narrative in nature. In addition to improving weed control, ecological strategies contribute to soil health, biodiversity conservation, reduced carbon emissions, lower energy use, and greater resilience under climate variability. The review covers literature published over recent decades, although an exact time frame and number of studies are not explicitly quantified. Although herbicides may still have a role in targeted situations, the review indicates that their judicious and complementary use within integrated systems is more sustainable than dependence on chemical control alone. Unlike previous reviews that focus mainly on individual practices, this study provides a broader synthesis of ecological mechanisms, system-level interactions and sustainability outcomes. Overall, ecological weed management provides a practical framework for developing productive, climate-resilient, and environmentally sound cropping systems.

1. Introduction

Weeds constitute one of the most persistent and pervasive biological constraints to agricultural productivity worldwide. They compete aggressively with crops for essential resources such as light, nutrients, water, and space, while also interfering with harvesting operations and deteriorating produce quality [1]. Beyond direct yield reductions, weeds impose substantial indirect economic burdens by increasing the cost of cultivation, reducing input-use efficiency, and limiting the productive potential of agricultural land. Globally, weeds are estimated to account for up to 34% of potential crop losses, underscoring their significant impact on food security and farm profitability [2]. In the Indian context, yield losses due to weeds are particularly severe, often ranging between 37–45%, and in extreme cases leading to complete crop failure. Weed management alone can account for nearly one-third of total cultivation costs, highlighting its central role in farm management decisions.

Historically, weed control has relied predominantly on chemical herbicides and intensive tillage practices. While these approaches have contributed to short-term productivity gains, their long-term sustainability has been increasingly questioned due to their high energy requirements, increased greenhouse gas (GHG) emissions, evolution of herbicide-resistant weed populations, degradation of soil structure,

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loss of soil organic carbon, decline in soil biodiversity, and potential contamination of water resources. These challenges Excessive and indiscriminate pesticide usage has resulted in herbicide resistance in over 269 weed species globally, as well as soil degradation, biodiversity loss, and water pollution [3].

Herbicides and tillage have played a crucial role in improving weed control efficiency, more labor requirements, and enhancing crop production and productivity in many agricultural Practices. However, their prolonged and intensive use has raised concerns about the evolution of herbicide-resistant weed populations, increased energy consumption, greenhouse gas emissions, soil structure degradation, depletion of soil organic carbon, and reduced agro-ecosystem resilience. Consequently, there is growing interest in integrated ecological weed management practices that maintain weed control effectiveness while minimizing environmental impacts [4].

In this context, ecological weed management (EWM) has emerged as a scientifically grounded and sustainable alternative that integrates ecological principles with agronomic practices. Rather than relying solely on curative measures, EWM emphasizes preventive and system-based strategies that manipulate crop–weed interactions to suppress weed populations [5]. Core practices include crop rotation, cover cropping, mulching, and biological control, which collectively reduce weed seed banks, disrupt weed life cycles, and enhance competitive crop advantage over time [6]. By promoting biodiversity, optimizing resource use, and leveraging ecosystem services, EWM not only mitigates environmental risks but also delays the development of herbicide resistance.

The urgency for transitioning toward ecological approaches is further intensified by the challenges posed by climate change. Alterations in temperature regimes, elevated atmospheric carbon dioxide concentrations, erratic precipitation patterns, and the increasing frequency of extreme weather events are expected to significantly influence weed dynamics. These changes can modify weed emergence patterns, alter crop–weed competition, disrupt the timing and efficacy of management interventions, and even affect herbicide performance [7, 8]. Consequently, conventional weed management strategies may become less reliable under changing climatic conditions.

Emerging literature strongly advocates for the adoption of resilient and adaptive weed management systems that can maintain functional stability under climatic uncertainty while conserving natural resources [4]. Ecological weed management aligns with these objectives by diversifying selection pressures, thereby reducing the likelihood of weed adaptation, and by enhancing system resilience through ecological intensification [9]. It provides a holistic framework that balances productivity, environmental sustainability, and economic viability.

Against this backdrop, a comprehensive and systematic review of ecological weed management practices is both timely and necessary. Such an analysis can consolidate existing knowledge, identify key ecological strategies, and highlight research gaps and implementation challenges, thereby contributing to the development of sustainable and climate-resilient agricultural systems.

Therefore, this review aims to examine ecological weed management strategies critically, elucidate the ecological mechanisms underlying weed suppression, assess their contributions to sustainable and climate-resilient agriculture, and identify key research needs for their wider adoption and future development.

2. Methodology

A systematic literature review approach was used to identify, screen, and synthesize literature addressing ecological weed management in relation to sustainability and climate resilience. The review focused mainly on peer-reviewed review and cited articles, analysis papers, and professionally relevant institutional or reputed publications published between 1995 and 2026 that explicitly mentioned ecological, agroecological, sustainable, or climate-resilient weed management techniques. A comprehensive literature search was conducted using major scientific databases, including Scopus, Web of Science, Google Scholar, and CAB Abstracts. Searches were performed using combinations of the following keyword strings: “ecological weed management,” “sustainable weed management,” “integrated weed management,” “climate-resilient weed management,” “weed ecology review,” and “conservation agriculture weed management.” The search process prioritized review and synthesis literature because the objective was to generate a manuscript-scale conceptual and evidence-based synthesis rather than a meta-analysis of uniform treatment effects. Information was extracted on publication focus, major weed management practices discussed, ecological mechanisms of weed suppression, sustainability outcomes, and climate-resilience implications. A narrative synthesis approach was adopted because the source base was heterogeneous in scope, study design, and reporting style, making formal quantitative pooling inappropriate.

2.1. Strategies Involved in Sustainable Weed Management

The reviewed literature consistently defines ecological weed management as a strategy that exploits ecological processes to reduce weed abundance, suppress recruitment, and increase crop tolerance of remaining weeds [10]. Rather than attempting total eradication, the approach aims to maintain weed populations below economically damaging thresholds while preserving ecosystem services and reducing the external costs of intensive chemical control [10, 11]. This framing is especially relevant to sustainable agriculture because it aligns weed control with broader goals of soil health, biodiversity conservation, and input efficiency. In order to prevent damage to the overall agricultural environment, it is necessary to implement an efficient and sustainable weed management strategy that integrates the various control techniques (such ascultural, mechanical, and biological) in a harmonic manner. This perspective emphasizes the integration of multiple weed control tactics rather than reliance on single-method interventions. This integration includes preventive, cultural, mechanical, biological and judicious chemical approaches operating in a complementary framework. We agree that the original statement could be interpreted as discouraging the use of beneficial technologies. Accordingly, the text has been revised to emphasize reduced reliance on herbicides and their judicious use within integrated and ecological weed management systems, while recognizing the potential role of precision agriculture and automation in improving weed management efficiency and sustainability. However, current evidence suggests that herbicides and mechanization can still play a selective and targeted role within integrated weed management systems when applied judiciously. Today, herbicide resistance in some weed biotypes is a serious issue that has to be addressed. However, the latest advancements in weed control technology have the potential to increase food production, decrease the quantity of inputs required, and lessen environmental harm, all of which will inevitably lead to more sustainable agricultural systems [12]. These advances include precision application technologies, sensor-based weeding systems and decision-support tools that enhance input efficiency while reducing environmental impact.

2.2. Cultural Practices

Through biomass production, residue persistence, and residue–nutrient interactions, cover crops have been demonstrated to enhance soil fertility and weed control; however, the strength and durability of these benefits vary depending on the environment. Globally, cultural weed management is among the most widely adopted approaches for weed control and encompasses practices such as stale seedbed preparation, crop rotation, enhancement of crop competitive ability, optimization of sowing and irrigation schedules, cover cropping, and intercropping [13].

Green Manure Crops

Green manures suppress weeds through multiple interacting mechanisms that operate during both the active growth phase and after termination. Understanding these mechanisms is fundamental to optimizing species selection, management timing, and integration with other weed control tactics. Competition for limiting resources represents one of the primary mechanisms by which actively growing green manures suppress weed establishment and growth. Cover crops that establish rapidly and produce high biomass effectively intercept light, deplete soil moisture, and take up available nutrients, thereby limiting resources available for weed germination and seedling development [14, 15]. The competitive ability of a cover crop depends on multiple factors including planting density, growth rate, canopy architecture, and rooting characteristics. Light competition is particularly important, as dense cover crop canopies can reduce light penetration to the soil surface to levels insufficient for photosynthesis by emerging weed seedlings. Studies have demonstrated that early establishment and rapid canopy closure are critical for maximizing competitive suppression. For example, in wheat systems, green manure crops that established early and produced high biomass significantly reduced weed density and biomass through resource competition [14, 15]. In comparison to the control, neither compost nor green manure raised overall weed biomass or density. The makeup of the weed community was greatly impacted by green manuring. Plots treated with green manure had increased relative densities of ruderal and competitive-ruderal species (based on Grime's categorization). In addition to benefiting maize in crop/weed competitive interactions, the use of green manure and innovative composting techniques also created favorable circumstances for undesirable weed species like competitive-ruderals. Green manuring can improve crop competitiveness by increasing nitrogen availability in the early stages of maize development.

Crop rotation and Intercropping

Intercropping represents an alternative cover cropping approach that integrates weed suppression with simultaneous cash crop production. A field trial in the Cherkasy region of Central Ukraine evaluated clover intercropping in sunflower crops during the 2023 growing season. The intercrop vegetation cover significantly reduced weed numbers and herbicide requirements. Intercropping positively affected sunflower yields, leading to consistently high yields without large cost increases. The climate resilience benefits of intercropping were particularly evident during drought stress. Intercrops improved soil moisture levels, preserving moisture during the growing season, with this effect especially noticeable during periods of drought by reducing moisture evaporation. The improved soil moisture conservation contributed to maintaining crop productivity under water-limited conditions. Beyond weed suppression and moisture conservation, intercrops improved soil fertility through increased organic matter content, with organic residues of clover increasing the biological activity of the soil. Intercrops also improved soil structure and contributed to the development of soil microbiota, ensuring better nutrient absorption. As anticipated, our findings show that intercropping may improve soil physical fertility and prevent erosion while significantly lowering the usage of herbicides without sacrificing sugarcane output or quality. These results support intercropping's potential as a sustainable strategy in intensive sugarcane systems' agro-ecological transition. But we also highlight important trade-offs, most notably the increased labor and output costs related to companion crop management. The discovery of rising weed pressure and changes in the makeup of weed communities over time is a significant finding of this study [16]. To improve soil health and inhibit weed growth, important management techniques include mulching, intercropping, crop rotation, residue assimilation, and cover crops [17].

Crop Establishment and Nutrient Management

Four crop establishment techniques—conventional puddled transplanted rice followed by conventional till wheat, conventional till direct-seeded rice followed by conventional till wheat, conventional till direct-seeded rice followed by zero till wheat with rice residue retention, and zero-till direct-seeded rice followed by zero till wheat with rice residue retention—as well as three nutrient management techniques—farmer's practice, recommended fertilizer dose, and Rice–Wheat Crop Manager (RWCM)-based site-specific nutrient management. In comparison to standard establishment methods, the results showed that zero-till direct-seeded rice and zero-till wheat with residue retention greatly increased plant height, tiller density, dry matter accumulation, leaf area index, and chlorophyll content at different growth stages and weed suppression [18].

Seed Rate

Among the evaluated sowing techniques, broadcasting resulted in the highest uptake of nitrogen (N), phosphorus (P), and potassium (K) by sesame. This enhanced nutrient absorption was attributed to the higher plant population achieved with a seed rate 1.5 times that used in other sowing methods, which may have increased overall nutrient uptake from the soil [19].

2.3. Physical Methods of Weed Management

Physical and mechanical methods (including thermal flame and laser tools and sensor-guided mechanical weeding) can remove weeds effectively without herbicide inputs, though their field accuracy depends on high-precision navigation and machine vision technologies. Conventional chemical herbicides remain widely used because they provide broad-spectrum control and operational simplicity, but they contribute to environmental pollution and select for herbicide-resistant weed populations. Combining nonchemical tactics with targeted, site-specific application (mapping, sensors, and selective spraying) can preserve control efficacy while reducing overall herbicide use [20, 21].

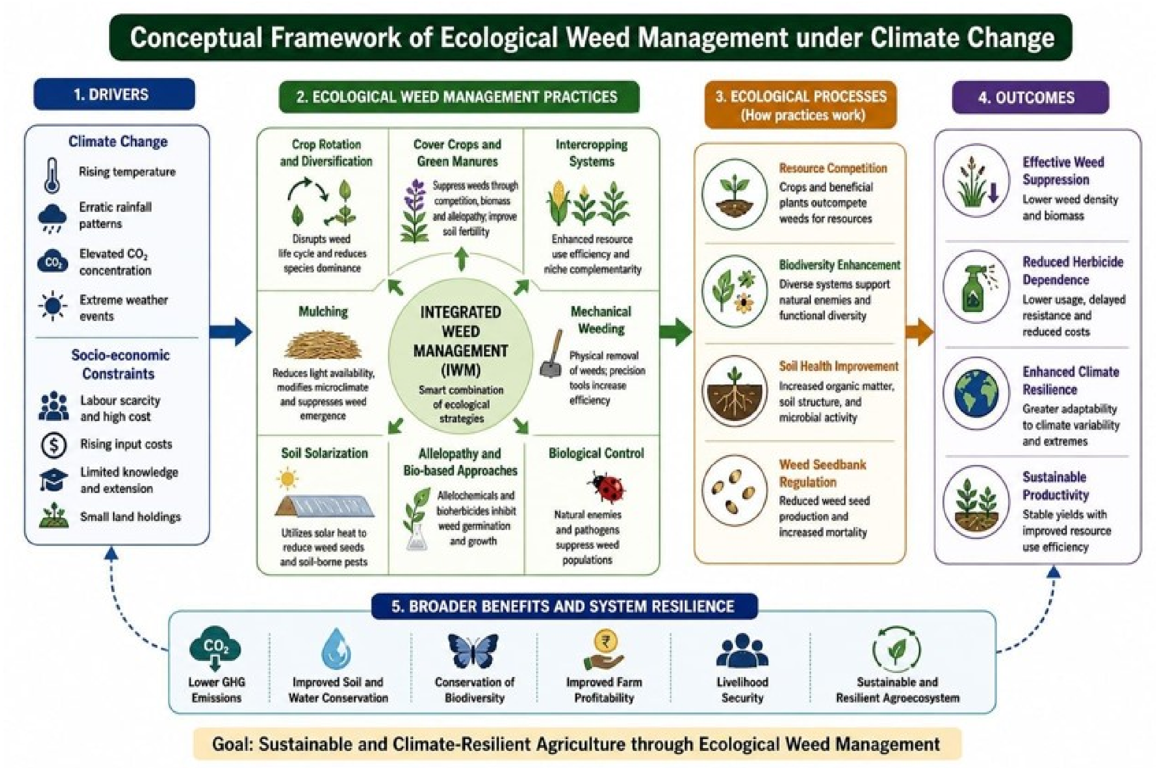

Figure 1: Ecological weed management strategies for sustainable agriculture

Physical force their control weed management through mechanical or animal power, manual to improve soil health and inhibit weed growth, important management techniques include mulching, intercropping, crop rotation, residue assimilation, and cover crops. Additionally, it has been noted that pesticide resistance is developing widely. Our perspectives on weed control have undergone a ”learning cycle.” At the conclusion of this learning cycle, a tendency toward managing weeds holistically has emerged [22].

Soil Solarization

In comparison to other approaches, soil solarization is an inexpensive, chemical-free technique. Soil solarization consistently reduces many annual weed species, often boosting crop yields, but effects are species specific and some perennials persist. Studies report strong control with clear polyethylene and ancillary benefits to soil fertility and reduced chemical use. Many soil borne diseases, plant-parasitic nematodes, and weeds have been demonstrated to be effectively managed by this method; however, its effectiveness in controlling arthropod pests and enhancing crop production and quality has been inconsistent. A straightforward, secure, economical, and environmentally beneficial method of controlling weeds in *Abelmoschus esculentus L.* is soil solarization. Unfortunately, the majority of farmers in our nation are unaware of the use of soil solarization technology for safe crop production and weed control [23]. Soil solarization studies show strong overall reduction of weed density and biomass, with efficacy depending on duration, film type, and weed biology. The five leading field studies report high control of many annuals, partial control of some perennials, and occasional stimulation of certain species.

Utilization of Weeding Implements

Across diverse crops and regions, mechanized and animal-powered implements typically improved weeding efficiency and reduced labor relative to manual weeding: ox-drawn SAARI weeders achieved very high weeding efficiency (95%) and higher groundnut yields (1135 versus 691 kg/acre) with greater gross margins compared with hand weeding, while an alternative ox-weeder (AEATRI) performed less well (65%) [24]. Precision mechanical systems (automatic steering/precision hoeing) substantially lowered weed densities ($\approx$ 89% in soybean, $\approx$87% in sugar beet) and increased yields ($\approx$23% soybean, $\approx$37% sugar beet) relative to conventional mechanical control, illustrating that guidance and speed gains can amplify efficacy and productivity. Broader integrated approaches combining cover crops, living mulches and sensor-assisted mechanical control reduced weed pressure (cover crops up to $\sim$ 66% suppression) and enabled herbicide reductions within integrated weed management frameworks [25]. Implement choice also involves draft and durability tradeoffs: some cultivators gave higher field efficiency ($>$90%) but required greater draft forces and maintenance, whereas mould-board options provided higher weeding efficiency and soil moisture retention and, combined with winter ploughing, improved yields and returns in cotton systems [26]. In organic peanut systems, repeated tine and sweep cultivation regimes combined with targeted hand weeding produced season-long control with favorable cost-effectiveness relative to hand weeding alone. In flooded rice, inter-row rotary weeders outperformed cono weeders in efficiency ($\approx$79% versus 72.5%) but differed in ergonomic energy demands and crop damage risk, highlighting species-and system-specific tradeoffs. These devices use rotating changes to cultivate and eradicate weeds between the rows. It lowers maintenance expenses and labor expenditures. With a blade fastened to the weed's roots, a human-powered weeder advances. The equipment removes weeds from the entire cultivated area by rotating its blades. The primary benefit is lower labor costs due to fewer employees and less time spent. Overall, the evidence shows consistent gains in efficiency and labor savings from mechanized or precision implements, but optimal choice depends on crop architecture, row spacing, soil/stony conditions, draft power availability, and tradeoffs among speed, energy/fuel use, and within-row control.

Table 1: Effect of soil solarization on weed management and crop yield under different studies

Study	Crop and setting	Solarization details	Weed control outcome	Notable weeds affected	Yield or crop effect
Singh 2003	Wheat in soybean-wheat system	Clear polyethylene; up to 5 weeks; surface temps to $\sim 56^{\circ}C$	68.8% reduction in weed population and 70.8% reduction in weed dry weight with 5-week solarization	Most weeds reduced; *Convolvulus arvensis* was not controlled	Grain yield increased to 5038 kg$\cdot ha^{-1}$ (≈27% over control)
Delpeche & Isaac 2013	Cabbage field trials	Clear 4 mm polyethylene for 7 weeks; some plots amended with manure	Clear plastic provided $\sim$97.6% weed control; clear+manure $\sim$96%	Broad weed suppression across the seedbank	Clear plastic plots yielded $\sim$36.45 t$\cdot ha^{-1}$ (highest)
Marenco & Lustosa 2000	Carrot on sandy soil	Transparent films for 0-9 weeks	Solarization reduced biomass/density in $\sim$50% of recorded species; 9 weeks most effective	Controlled *Cyperus spp.* and several annuals; *Commelina benghalensis* germination increased	Marketable carrot yield higher in solarized plots
(Candido et al., 2011)	Lettuce field and greenhouse	Multiple film types including LDPE, EVA, coextruded and biodegradable	Strong reduction of weed density and biomass; most annuals largely controlled	Perennials largely unaffected except Cirsium arvense; Amaranthus spp. escaped with biodegradable film	Lettuce yield significantly higher after solarization; film type had little effect on yield

Mulching

Synthetic and biodegradable mulches most consistently suppress weeds and boost yields across diverse crops, while organic and waste mulches can be effective but show variable persistence and species-specific outcomes. Choice should match crop, site, and mulch durability. Mulching is generally used to saved water and control weed germination and weed growth suppression and improve the soil around plants and increase along with fertility, moisture and microbial activity with their ability to affect weed dynamics, soil fertility, and agro-ecosystem resilience, cover crops are becoming more widely acknowledged as multipurpose elements of sustainable cropping systems. Nevertheless, the data compiled in this analysis demonstrates that these advantages are not shared by all species and that results are highly dependent on environmental factors, management choices, and species characteristics [13]. Across the studies, synthetic films and geotextiles delivered the strongest, most consistent weed suppression and concomitant yield gains: Chib [27] recorded 99.75% weed control efficiency and markedly higher persimmon yield under black polyethylene. Atieno [28] found black polythene produced the tallest French bean plants and highest pod yields (2138–2597 kg/ha) versus grass mulch or hand-weeding and Ocharo [29] observed that black plastic gave the lowest weed species count and biomass in green pepper trials. Biodegradable much sheets provided the best trade-off between suppression and crop yield in organic systems in [30]. Organic mulches often reduced weed biomass and improved yields but showed variable longevity and species effects: Yordanova and Gerasimova [31] observed 8–10× beetroot yields versus unweeded controls and modest gains over hand-weeding with barley straw or spent mushroom compost whereas Hristova (2024) found compost mulch benefits waned and sometimes increased weeds over time while sand mulch remained effective for meadow establishment. Among waste and unconventional mulches, paper mulch produced the lowest weed dry weight and best tomato yields in Usanmaz-Bozhüyük [32] and Duarte dos Santos et al. (2025) found straw most effective in restoration beds while castor-bean mulch provided poor coverage and control. Thakur and Upadhyay [33] evaluated mulching in kharif sorghum systems but the available record here offers limited extractable metrics. Overall, films and geotextiles give rapid, strong suppression and yield benefits across crops, biodegradable films can reconcile organic-system goals, and organic/waste mulches are promising but more variable in durability and species-specific performance.

2.4. Bio-based Weed Control Methods

In order to create the next generation of bio-herbicides as a viable option for long-term weed control, this perspective paper suggests and explores the possibilities of a novel strategy that blends living microbes with botanical components in symbiotic formulations. Because of the synergistic interactions that result from complimentary and/or cooperative effects, their combination may be more effective than using each of them separately. Future studies should concentrate on developing new bioherbicidal strains, increasing field consistency, developing formulation technology, and incorporating biological control into comprehensive weed management systems. Researchers, legislators, and business stakeholders must work together to overcome technological and financial obstacles.

Allelopathic Plant

Allelopathy is a natural process in which plants generate chemicals (allelochemicals) that affect other plants' development, providing environmentally acceptable alternatives for sustainable farming and weed control.

Table 2: Allelopathic interactions for suppression of competing weeds

Allelopathic Plant/Weed	Major Allelochemicals	Target Weeds Affected	Mode of Action
Ageratum conyzoides	Flavonoids, phenolics	Annual weeds	Reduces germination and early growth
Parthenium hysterophorus (Congress grass)	Parthenin, phenolics	Grasses and broadleaf weeds	Inhibits seed germination and seedling growth
Chenopodium album (Bathua)	Phenolic acids	Broadleaf weeds	Interferes with seed germination
Imperata cylindrica (Cogon grass)	Phenolic compounds	Crop-associated weeds	Reduces seedling establishment

Table 3: Weed species managed through insect bio-control agents

Weed Species	Common Name	Insect Agent Use	Modes of Action
Opuntia spp.	Prickly pear cactus	*Cactoblastis cactorum*	Larvae bore into stems causing plant death
Eichhornia crassipes	Water hyacinth	*Neochetina eichhorniae / N. bruchi*	Adults and larvae feed on leaves and petioles
Parthenium hysterophorus	Congress grass	*Zygogramma bicolorata*	Defoliates leaves, reducing growth and seed production
Salvinia molest	Water fern	*Cyrtobagous salviniae*	Larvae damage buds and rhizomes
Cirsium arvense	Canada thistle	*Urophora cardui*	Forms galls, reducing plant growth

Table 4: List of microorganisms used in bio-herbicides and their target weeds and ecosystems

Microorganism	Trade Name	Target Weed	Use Area
Phytophthora palmivora	DeVine	Morrenia odorata (milkweed vine)	Citrus orchards, plantations
Colletotrichum truncatum	BioMal	Malva pusilla (round-leaved mallow)	Wheat and barley fields
Alternaria cassiae	CASST	Cassia obtusifolia (sicklepod)	Soybean fields

Bio-Fertilizer

The study shows that under mustard cultivation, applying bio-fertilizers in conjunction with appropriate fertilizer dosages increases crop output while preserving the physio-chemical characteristics of the soil [34].

Herbicide Resistant Crop

Non-target creatures may be impacted by herbicide residues in the soil, and runoff into rivers, streams, and other bodies of water may damage aquatic ecosystems and could disrupt supplies of drinking water. Insects and other creatures that depend on those plants for food and habitate may be impacted by the decreased plant biodiversity in agricultural areas caused by the more effective weed control provided by HTCs [18].

3. Integrated Weed Management

Integrated Weed Management (IWM) is characterized as a multitactical, systems-level strategy that combines preventive, cultural, mechanical, biological, and chemical tools to manage weed populations rather than aiming for eradication, with emphasis on reducing selection pressure for herbicide resistance and enhancing agroecosystem functions. Multitactic integration combines crop rotation, cover crops, tillage/modulation of soil disturbance, competitive cultivars, and direct control (mechanical/targeted chemical) to create diverse selection pressures on weeds. Comparative performance shows integrated systems can deliver similar or better agronomic outcomes and higher combined sustainability metrics than conventional and organic systems when alternative practices are implemented systematically [35]. In order to control weeds sustainably and lessen the need for pesticides to reduce resistance, non-chemical integrated weed management (IWM) employs cultural, mechanical, and biological strategies. Cover crops, crop rotation, mechanical cultivation, mulching, soil solarization, and grazing are important techniques. In order to reduce environmental harm and ecological disruption, the IWPM integrates cultural, mechanical, biological, and careful chemical procedures through the use of biotechnological tools and precision farming. Climate change, the invasion of other species, and the emergence of pest resistance are just a few of the new difficulties that need management to be flexible and adaptable while sticking to scientific advancements and ecological principles [36].

4. Conclusion

Ecological weed management represents a shift from weed eradication toward long-term population suppression through agronomic, biological, mechanical, and ecological processes. The reviewed evidence indicates that no single tactic is universally sufficient, but combinations of practices can substantially reduce weed pressure while supporting soil quality, resource-use efficiency, and farm resilience. Among the most effective approaches are crop diversification, competitive cultivars, cover crops, mulching, conservation tillage, precision mechanical weeding, and biologically based interventions, especially when these are adapted to crop, weed, and site conditions. The review also highlights that climate change, herbicide resistance, labor constraints, and environmental concerns make diversified weed management increasingly necessary. Future progress will depend on stronger integration of ecological knowledge, precision tools, and site-specific management, along with greater extension support and farmer adoption of multi-tactic weed control systems.

Article Information

Disclaimer (Artificial Intelligence): The authors declare that generative artificial intelligence (AI) tools, including Gemini Pro and NotebookLM, were used solely for the purpose of creating illustrative figures and conceptual diagrams presented in the manuscript. These tools were employed responsibly and ethically, based strictly on the scientific evidence and literature cited in the manuscript. No AI tools were used for generating, interpreting, or modifying the scientific content, results, or conclusions.

Competing Interests: Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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