CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT

GLOBAL ISSUES & LOCAL PERSPECTIVES

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PUPLISHED BY:

Society for Agriculture, Environmental Resources & Management (SAEREM)

SAEREM BOOK CHAPTERS First published 2026-- ISBN 978-978-60709-1-6@ SAEREM World

First published 2026

SAEREM World

Nigeria

Typeset in Times New Roman

CLIMATE SMART ACTIONS (CSA) AQUACULTURE, AGROFORESTRY AND RESOURCES MANAGEMENT--- ISBN 978-978-60709-1-6

Global Issues & Local Perspectives

Printed at: SAEREM World

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Preface

This book adopts an exegetical approach as well as a pedagogic model, making it attractive agriculture and environmental economics teachers, professional practitioners and scholars. It is eschews pedantry and lays bars the issues in such clarity that conduces to learning. The book elaborates on contemporaneous **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues of global significance and at the same time, is mindful of local or national perspectives making it appealing both to international and national interests. The book explores the ways in which **Climate smart actions (CSA) aquaculture, agroforestry and resources management** issues are and should be presented to increase the public's stock of knowledge, increase awareness about burning issues and empower the scholars and public to engage in the participatory dialogue **Climate smart actions (CSA) aquaculture, agroforestry and resources management** necessary in policy making process that will stimulate increase in food production and environmental sustainability. **Climate smart actions (CSA) aquaculture, agroforestry and resources management :** *Global Issues & Local Perspectives* is organized in three parts. Part One deals with The Concept of **Climate smart actions (CSA)**, Part Two is concerned with The Concept of **aquaculture,** and Part Three deals with the Concept of **agroforestry and resources management**

Eteyen Nyong; March 2026

Chapter 4:

Climate-Smart Weed Management Strategies for Sustainable Crop Production and Ecosystem Health

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1.0 INTRODUCTION

Agricultural production systems across the globe are increasingly threatened by climate change, including rising temperatures, elevated atmospheric CO_2, erratic rainfall patterns, prolonged droughts, flooding events, and shifting pest and weed populations. These changes undermine food security, particularly in tropical and sub-tropical regions where resource-poor farmers depend heavily on rain-fed agriculture and have limited adaptive capacity (FAO, 2021). Climate change directly affects weed ecology by altering germination, growth rates, and competitive interactions between crops and weeds. Elevated CO_2 can enhance photosynthesis, biomass production, and water-use efficiency in many C_3 weed species, while rising temperatures may favor thermophilic C_4 weeds. Altered precipitation patterns further influence weed community composition and geographic distribution (Kaur et al., 2024; Mouetel et al., 2023).

Weeds possess high genetic variability, phenotypic plasticity, rapid reproductive cycles, and efficient dispersal mechanisms, enabling them to adapt quickly to environmental change. These traits may confer a competitive advantage over cultivated crops under future climate scenarios, intensifying crop–weed interference and leading to substantial yield losses (Kumar et al., 2023; Lau & Funk, 2023). Additionally, climate-induced changes in plant morphology and physiology may reduce herbicide effectiveness and accelerate resistance evolution, complicating management strategies (Parvati et al., 2024; Mou et al., 2025).

Despite these risks, many crop productivity models do not adequately incorporate weed dynamics, potentially underestimating projected yield losses under climate change (Shahzad et al., 2021; Storkey et al., 2021). A clearer understanding of weed ecological and physiological responses to changing climatic conditions is therefore essential for developing adaptive and sustainable weed management strategies.

1.1 Climate-Smart Agriculture and the Need for Transformative Weed Management

The emerging concept of Climate-Smart Agriculture (CSA) provides an adaptive framework to address these challenges by promoting sustainable increases in productivity, enhanced resilience to climate shocks, and reduction of greenhouse gas (GHG) emissions while maintaining ecosystem integrity (FAO, 2022). Rather than focusing solely on yield maximization, CSA emphasizes the need to balance productivity with environmental sustainability and long-term system stability. It recognizes that agricultural practices must be flexible, knowledge-driven, and responsive to changing climatic conditions. Within this framework, weed management traditionally viewed primarily as a yield protection activity must evolve into a climate-responsive, resource-efficient, and ecologically aligned strategy. Weeds are not only competitors for nutrients, water, and light; they are dynamic biological components whose behavior is strongly influenced by climatic variables such as temperature, carbon dioxide concentration, and rainfall variability. As climate change alters weed emergence patterns, growth dynamics, and herbicide sensitivity, conventional control methods become less predictable and potentially less effective (Storkey et al., 2021).

Conventional herbicide-intensive approaches, while effective in the short term, contribute to GHG emissions, biodiversity loss, herbicide resistance development, and soil degradation, thereby counteracting the sustainability goals of CSA (Monteiro & Santos, 2022). Overreliance on chemical inputs can disrupt soil microbial communities, reduce ecosystem services, and increase production costs for farmers, especially in resource-constrained settings (Țopa et al., 2025). In the long term, such approaches undermine the resilience of farming systems by creating dependency on external inputs and limiting ecological buffering capacity.

Transformative weed management under CSA therefore requires a shift from reactive control to proactive system design. It involves integrating ecological principles, improving crop competitiveness, enhancing soil health, and promoting diversified cropping systems that naturally suppress weed proliferation. By aligning weed management strategies with climate adaptation and mitigation objectives, agriculture can transition toward systems that are not only productive but also resilient, regenerative, and environmentally responsible.

1.2 Integrating Climate-Smart Agriculture and Integrated Weed Management

Integrated and climate-smart weed management therefore emphasizes ecological balance, adaptive practices, and innovation, linking weed suppression to soil health, water conservation, and biodiversity enhancement (Bouri et al., 2023). This integration includes cultural and mechanical practices such as crop diversification, mulching, conservation tillage, biological control, and precision agriculture, which together minimize external input use and strengthen system resilience. Emerging evidence shows that combining CSA and Integrated Weed Management (IWM) approaches reduces production risk, enhances carbon sequestration through cover crops, and supports long-term soil fertility and productivity (Rudell et al., 2023; Olarewaju al., 2025).

In essence, climate-smart weed management forms a critical pillar of sustainable agricultural intensification. It aligns the goals of weed suppression with broader environmental and climate objectives reducing input dependency, conserving biodiversity, and fostering adaptive capacity among farming communities. As global agriculture transitions toward low-carbon pathways, embedding weed management within the CSA framework ensures that production systems not only maintain yields under climatic stress but also contribute to climate mitigation and environmental stewardship (Gabriel et al., 2023; Moutel et al., 2025).

2. Climate Change and Weed Dynamics

Weed ecology is profoundly shaped by climatic variables, and the ongoing shifts in global temperature, precipitation, and atmospheric CO_2 concentration are redefining weed–crop interactions, distribution, and management strategies. Among all biotic constraints, weeds are likely to be the most responsive group to climate perturbations due to their high reproductive capacity, short life cycles, and physiological plasticity (Kumar et al., 2023; Kaur et al., 2024). Rising CO_2 levels, erratic rainfall, and fluctuating temperatures modify not only the growth and phenology of weed species but also their geographical distribution and invasiveness, enabling certain aggressive species to colonize previously unsuitable environments (Kassam et al., 2022).

2.1 Elevated CO_2 and Weed Competitiveness

The increase in atmospheric CO_2 concentration, projected to exceed 600 ppm by 2050, alters photosynthetic efficiency, carbon allocation, and water-use dynamics in both crops and weeds. However, weeds often show a stronger growth response to elevated CO_2, particularly through enhanced leaf area expansion, biomass accumulation, and reproductive output (Kaur et al., 2025; Olarewaju et al., 2025). These physiological changes may intensify interspecific competition for light, water, and nutrients, tipping the competitive balance in favor of weeds, especially in nutrient-rich or poorly managed fields. Experiments have shown that under elevated CO_2, species such as *Amaranthus retroflexus* and *Chenopodium album* exhibit 30–50% higher biomass and seed production than associated cereal crops (Kaur et al., 2024).

2.2 Temperature and Precipitation Variability

Temperature increases accelerate weed metabolic activity and shorten growth cycles, allowing multiple generations per season and faster replenishment of the soil seed bank. In contrast, higher night-time temperatures promote enhanced respiration and carbohydrate mobilization, further supporting weed growth relative to crops with narrower thermal optima (Oleti et al., 2024). Moreover, altered precipitation regimes such as extended droughts and sporadic intense rainfall favor opportunistic weeds capable of rapid germination following moisture availability. Such climatic extremes enhance the prevalence of drought-tolerant species like *Cyperus rotundus* and *Sorghum halepense*, which thrive under moisture-stressed conditions and outcompete water-sensitive crops (Wang et al., 2025).

2.3 Photosynthetic Pathways and Adaptive Responses

Differences between C_3 and C_4 photosynthetic pathways profoundly influence weed competitiveness under changing climate scenarios. Elevated CO_2 levels generally enhance photosynthesis in C_3 species (e.g., *Chenopodium album*, *Phalaris minor*), while C_4 weeds (e.g., *Echinochloa crus-galli*, *Amaranthus spp.*) gain greater advantage under high-temperature and water-stress conditions (Manisankar & Ramesh, 2019). Consequently, shifts in climatic variables are expected to cause changes in dominant weed flora within major cropping systems, often replacing low-temperature C_3 weeds with thermophilic C_4 species in tropical and subtropical regions. This ecological rebalancing complicates control measures and necessitates site-specific, adaptive weed management tailored to evolving climate conditions.

2.4 Mechanistic and Ecological Implications

Climate change also influences weed–crop competition through phenological mismatches, extended germination windows, and altered herbicide efficacy. Elevated temperatures accelerate weed emergence earlier than crops, granting weeds an early-season advantage in resource capture (Gabriel et al., 2023). Concurrently, increased CO_2 can reduce herbicide absorption due to thicker leaf cuticles and altered stomatal behavior, diminishing chemical control effectiveness (Anwar et al., 2021). Such factors, compounded by unpredictable rainfall patterns, may render traditional weed management approaches less effective, requiring integrated strategies that emphasize ecological resilience, crop competitiveness, and adaptive timing of control measures (Kaur et al., 2024; Chirilli et al., 2025).

Overall, the interplay of CO_2 enrichment, temperature rise, and precipitation variability contributes to evolving weed communities characterized by higher plasticity, broader geographical ranges, and resistance to conventional management. This dynamic underscore the urgent need for climate-smart, ecosystem-based weed management frameworks that integrate adaptation, mitigation, and biodiversity principles for sustainable agricultural production in the face of climate change.

3. Environmental Impacts of Conventional Weed Control and Weed Proliferation

Weed proliferation and conventional weed control practices have profound environmental implications that extend beyond crop yield loss, influencing ecosystem health, soil quality, water systems, biodiversity, and climate resilience. In agricultural systems, weeds compete directly with crops for light, water, and nutrients, reducing yields and increasing the need for management inputs, thereby amplifying environmental pressures (Kubiak et al., 2022; Naeem, et al., 2022). For example, studies show that under drought and climate stress conditions, weed competition can exacerbate crop water deficits, leading to more severe yield losses (Lami et al., 2025).

3.1 Weed Impacts on Ecosystem Services and Biodiversity

While weeds are often defined by their negative effects on crops, they also play complex roles in agroecosystems. High weed densities can reduce the ecological resilience of cropping systems by displacing native flora, altering habitat structure, and reducing overall biodiversity Leguizamón, 2024). Over reliance on herbicides and simplified crop monocultures have led to dramatic declines in weed diversity, which has undermined ecosystem functions such as pollination, nutrient cycling, and soil microbial activity (Boinot et al., 2024).

At the same time, some weed species act as ecosystem engineers with multifaceted roles. For instance, invasive species such as *Tithonia diversifolia* may dominate landscapes and reduce forage quality, yet in some ecological contexts they contribute to soil remediation or biomass production (Rai et al., 2023; Boinot et al., 2024). However, these benefits are highly context-specific and often cannot offset the broader ecological and agronomic costs associated with weed invasion.

3.2 Soil, Water, and Chemical Footprint

Conventional weed management, particularly chemical control, has both benefits and drawbacks. While herbicides can efficiently reduce weed pressure and increase yields, their use contributes to environmental risks, including contamination of surface and groundwater, non-target impacts on soil microorganisms, and potential threats to wildlife and human health (Ziyanayi et al., 2024; Parven et al., 2025). Continued and high-rate herbicide application also fosters herbicide resistance, a major challenge that reduces control effectiveness and often leads to higher chemical input cycles (Shackleton et al., 2019; Shakya et al., 2022). In addition to chemical concerns, frequent tillage and weed removal disturb soil structure, promoting erosion, carbon release, and loss of soil organic matter. These processes compromise soil health and reduce its capacity to sequester carbon, undermining broader climate mitigation efforts.

3.3 Weed Interactions under Climate Stress

Climate change intensifies the environmental impacts of weeds by increasing their adaptive potential and competitive edge under stress conditions. As noted in recent research, weeds are confirmed as major biotic limiting factors in climate change scenarios, especially under conservation tillage where weed pressure is often higher (Lami et al., 2025). Weeds often maintain or even increase their competitive effects under drought and heat stress, leading to disproportionate crop losses compared to well-managed conditions (Savić et al., 2025).

3.4 Herbicide Reduction and Ecosystem Trade-offs

Recent studies also highlight a growing interest in reducing herbicide usage to enhance agroecosystem biodiversity and resilience. Strategies such as site-specific spraying, species-specific dose rates, and use of selective herbicides aim to limit environmental impacts while maintaining weed control efficacy (Upadhyay et al., 2024; von Redwitz et al., 2025). According to Ramens et al (2022), such approaches align with climate-smart and agroecological management paradigms that prioritize ecosystem services alongside crop productivity.

3.5 Integrated and Ecological Weed Management

Conventional weed management practices, particularly heavy reliance on herbicides and frequent tillage, have contributed to environmental degradation through the loss of soil biodiversity, contamination of water resources, and disruption of ecosystem resilience. Moreover, climate change intensifies these challenges altered rainfall patterns, increased temperatures, and erratic weather events can influence herbicide efficacy by modifying plant absorption, translocation, and metabolic processes, thereby making chemical control less reliable and predictable (Kumar, 2024).
In addition, repeated soil disturbance associated with conventional tillage releases stored carbon into the atmosphere, increasing greenhouse gas emissions and undermining broader climate-mitigation goals.

In response to these growing concerns, Integrated Weed Management (IWM) and ecological weed control strategies have emerged as key components of sustainable and climate-smart agricultural systems. These approaches combine cultural, biological, mechanical, and chemical methods to manage weeds below economic thresholds while preserving environmental integrity (Dar et al., 2022; Maqbool et al., 2022). Practices such as cover cropping, crop rotation, timely mechanical weeding, and the use of allelopathic microbes or bio-herbicides help suppress weeds naturally, improve soil structure, and enhance microbial diversity. Precision technologies such as site-specific herbicide application and remote sensing-based weed mapping further reduce chemical dependency and improve control efficiency (Verdugo-Navarrete et al., 2021).

Adoption of IWM and ecological methods not only mitigates the environmental footprint of weed management but also promotes soil health, water quality, and biodiversity conservation, which are critical for building climate resilience. By integrating these diverse techniques, farmers can achieve sustainable weed suppression while enhancing resource-use efficiency and ecological stability. Ultimately, such integrated systems align closely with the Climate-Smart Agriculture (CSA) framework, which seeks to simultaneously improve productivity, strengthen adaptation capacity, and reduce greenhouse gas emissions within agricultural landscapes.

4. Principles of Climate-Smart Weed Management

Climate-smart weed management (CSWM) represents a comprehensive framework that aligns weed control strategies with the three core pillars of Climate-Smart Agriculture (CSA): increased productivity, enhanced resilience, and reduced greenhouse gas emissions. It emphasizes ecologically sustainable interventions that conserve resources, optimize efficiency, and adapt to the biophysical uncertainties imposed by climate change. These principles are underpinned by the recognition that weeds are not only biological competitors but also drivers of agroecosystem imbalance and contributors to environmental degradation through their influence on nutrient cycling, soil structure, and biodiversity dynamics

4.1 Integrated Weed Management (IWM)

Integrated Weed Management (IWM) serves as the cornerstone of climate-smart approaches, combining cultural, mechanical, biological, and chemical tactics in a harmonized manner to manage weed populations below economic thresholds. Unlike single-method dependence, IWM leverages the synergy among various practices crop rotation, intercropping, mulching, and the use of competitive cultivars to suppress weed growth while maintaining ecosystem stability (Maqbool et al., 2022; Kumar et al., 2023).

Research under tropical and semi-arid conditions shows that diversified rotations incorporating legumes and cover crops enhance nitrogen cycling, improve canopy closure, and disrupt weed reproductive cycles, thereby reducing the need for synthetic herbicides (Sosnoskie et al., 2023). Similarly, the integration of allelopathic crops and bio-herbicides supports biological weed suppression while lowering environmental toxicity. This integrated framework ensures that weed control not only protects yield but also contributes to carbon sequestration, soil microbial diversity, and water-use efficiency, reinforcing the climate resilience of farming systems.

4.2 Conservation Practices

Conservation-oriented management underpins Climate-Smart Weed Management (CSWM) by maintaining soil cover, enhancing organic matter, improving soil structure, and minimizing soil disturbance. Practices such as reduced or zero tillage, residue retention, and cover cropping influence weed seed bank dynamics and crop–weed interactions by modifying the soil microenvironment (Jat et al., 2022; Verma et al., 2024). Reduced tillage limits soil inversion and light exposure, which can decrease the germination of certain weed species over time, particularly when integrated with complementary practices.

Residue retention and mulching suppress light-dependent weed germination by limiting light penetration to the soil surface, moderating temperature fluctuations, and conserving soil moisture an important benefit in drought-prone regions (Singh et al., 2023). The physical barrier created by crop residues further restricts weed seedling emergence and reduces early weed vigor. Cover crops enhance suppression through competition for light, water, and nutrients, and in some cases through allelopathic effects, while dense canopies reduce photosynthetically active radiation reaching the soil surface during fallow periods. Additionally, conservation practices enhance soil biological activity by fostering microbial communities and soil fauna that indirectly inhibit weed seedling establishment through ecological competition and allelopathic interactions. For sustained effectiveness, however, conservation systems should be integrated with diversified crop rotations and complementary weed management strategies to maintain long-term suppression under variable climatic conditions.

4.3 Precision and Technological Innovations

Technological advancement has revolutionized modern weed management by improving detection accuracy, minimizing input waste, and reducing the carbon footprint of farm operations. Precision agriculture tools, including unmanned aerial vehicles (UAVs), machine-learning-based weed recognition, and robotic spot spraying, have shown potential to reduce herbicide application by up to 70% while maintaining control efficiency (Li et al., 2023; Zhou et al., 2024).

Furthermore, smart sensors, Internet of Things (IoT) devices, and satellite-based decision support systems allow real-time weed mapping and predictive modelling of weed-crop competition, enabling site-specific interventions that optimize input use and limit environmental pollution (Ahmad et al., 2022). Integration of these technologies aligns weed management with low-emission agriculture, directly contributing to CSA's mitigation objectives.

4.4 Toward Adaptive and Climate-Responsive Weed Systems

A truly climate-smart weed management system is adaptive continuously responding to shifts in weed ecology induced by climate variability. Emerging models suggest integrating predictive climate analytics with on-farm data to anticipate weed population dynamics and tailor management responses accordingly (Zhang et al., 2024). Such adaptive systems support proactive decision-making, preventing yield losses while reducing unnecessary interventions.

In essence, the principles of Climate-Smart Weed Management advocate for a transition from reactive, input-intensive approaches toward resilient, knowledge-driven, and ecosystem-based systems, ensuring that weed control contributes not only to productivity but also to environmental sustainability and climate adaptation as stated by Xuan et al. (2025).

Table 1. Comparative Overview of Climate-Smart Weed Management Practices

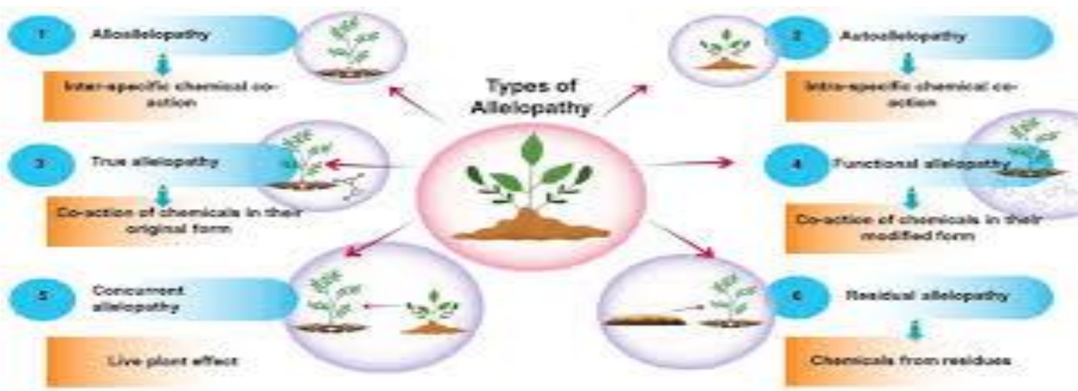
CSA Principle	Core Practices	Key Benefits	Climate-Smart Outcomes
Integrated Weed Management (IWM)	Crop rotation, cover crops, biological control	Reduced weed pressure, minimized herbicide use	Improves resilience, enhances biodiversity
Conservation Practices	Minimum tillage, residue retention, mulching	Better soil structure, suppressed weed germination	Carbon sequestration, reduced GHG emissions
Precision and Technological Innovations	UAV-based mapping, robotic weeding	Targeted control, efficient resource use	Lowers energy footprint, reduces chemical input

5. Agroforestry and Weed Suppression

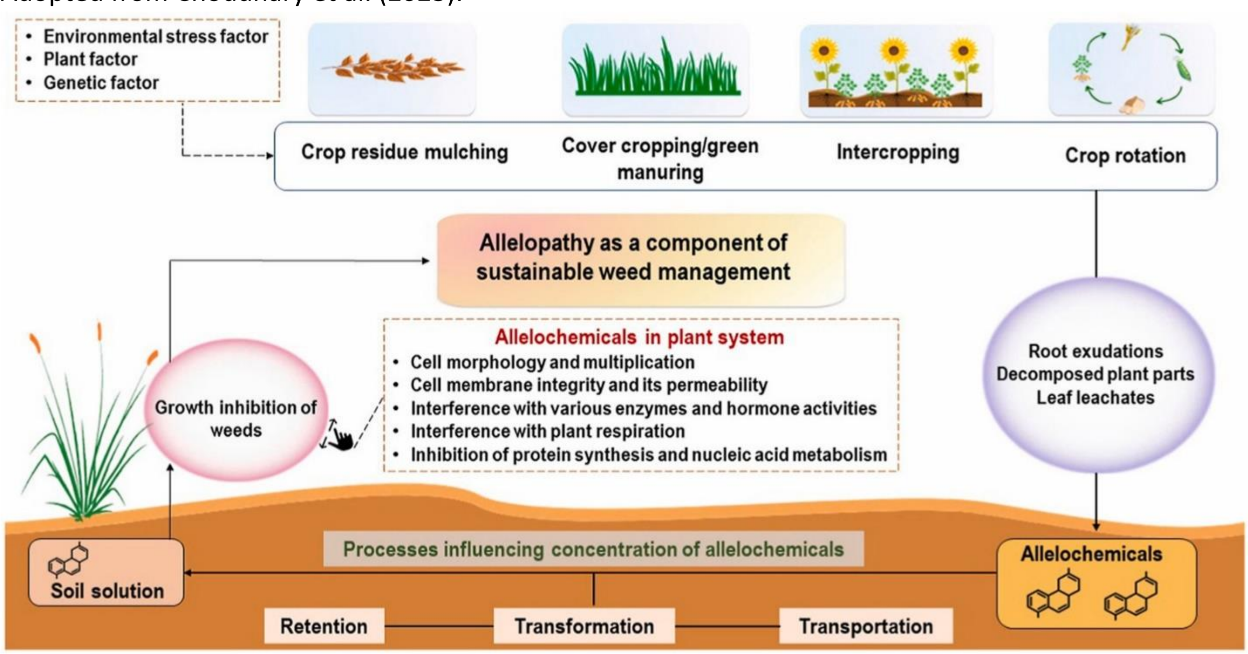
Agroforestry systems integrating trees, shrubs, and crops within the same landscape serve as an ecologically sound and climate-smart approach to sustainable weed management. The presence of perennial tree canopies modifies the microclimate, reduces light intensity at the soil surface, and alters temperature and humidity conditions, all of which restrict the germination and growth of light-demanding weed species (Kaur et al., 2023). The shade effect created by trees and shrubs limits photosynthetically active radiation (PAR) reaching the soil, reducing the competitive advantage of fast-growing weeds that typically dominate open-field systems.

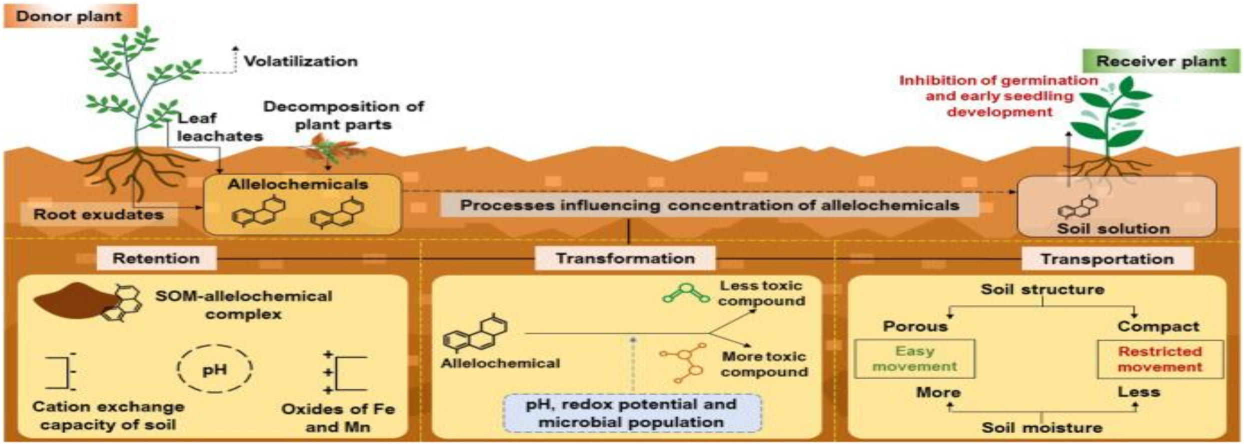
Furthermore, litter fall and root exudates from trees such as *Gliricidia sepium*, *Leucaena leucocephala*, and *Albizia lebbeck* contribute organic matter and may exhibit allelopathic effects, suppressing weed seed germination and early seedling development (Rahman et al., 2022). Over time, these mechanisms build up soil organic carbon, improve nutrient cycling, and enhance microbial diversity factors that strengthen the soil's ecological resistance to invasive weed species.

Agroforestry contributes to weed suppression through strategic resource competition and the modification of the soil environment. Deep-rooted trees extract nutrients and water from lower soil layers, while crops exploit upper layers, effectively reducing the resources available for weed proliferation (Fahad et al., 2022; Chaves et al., 2024).



Adopted from Choudhary et al. (2023).





Adopted from Choudhary et al. (2023).

Complementing these mechanisms, a study conducted by Chaves et al. (2024) revealed that management intensity and biodiversity levels significantly dictate the soil's physico-chemical and biological profile, as shown in Table 1 and 2. Specifically, rustic agroforestry systems demonstrated significantly higher Organic Carbon levels and C:N ratios compared to polyculture systems, indicating a robust accumulation of organic matter. This accumulation, along with tree litter, provides a physical barrier that inhibits weed emergence while simultaneously improving soil structure and moisture retention.

The research further indicated that while increased crop richness enhances soil conductivity, higher tree richness may lead to a significant reduction in potassium levels, suggesting intense competition for essential cations. Furthermore, the study found that increased canopy cover significantly fostered total microbial counts, pointing to a more biologically active soil environment. This enhanced microbial activity, protected by the canopy's microclimate, contributes to long-term soil health and creates a more competitive environment that naturally suppresses weed establishment.

Table 1: Physico-chemical properties of topsoil and subsoil under rustic and polyculture agroforestry systems in Western Bali.

Variables	Rustic Topsoil 0 to 5 cm	Rustic Subsoil 10 to 15 cm	Polyculture Topsoil 0 to 5 cm	Polyculture Subsoil 10 to 15 cm
pH	6.56 ± 0.11	6.59 ± 0.12	6.59 ± 0.15	6.51 ± 0.19
Conductivity (mS/cm)	0.61 ± 0.033	0.44 ± 0.19	0.77 ± 1.43	0.36 ± 0.18
Organic C (%)	3.17 ± 0.81	2.59 ± 0.57	2.46 ± 1.08	1.97 ± 0.71
Total N (%)	0.17 ± 0.08	0.17 ± 0.05	0.19 ± 0.06	0.15 ± 0.04
C:N ratio	32.34 ± 39.08	17.17 ± 7.62	13.66 ± 6.05	13.52 ± 6.17
Available P (ppm)	2.53 ± 2.84	2.61 ± 2.33	12.46 ± 13.36	14.83 ± 13.83
Available K (ppm)	174.04 ± 73.53	173.93 ± 71.17	244.76 ± 70.68	238.37 ± 73.58
Total microbes (x million)	88.50 ± 194.07	110.35 ± 204.92	5.79 ± 13.00	9.52 ± 20.44

Source: Adopted from Chaves et al. (2024).

Table 2: Descriptive statistics of the continuous fixed factors considered in this study

Factor	Mean	Std	Minimum	Maximum
Canopy cover (%)	29.2	19.0	0.5	71.9
Crop richness (n)	4.7	1.5	2.0	9.0
Tree richness (n)	2.1	2.2	0.0	7.0
Yields (USD/plot)	300.9	324.7	14.7	1844.3

Source: Adopted from Chaves et al. (2024).

When embedded within Climate-Smart Agriculture (CSA) frameworks, agroforestry-based weed management offers multiple co-benefits. It reduces dependence on synthetic herbicides, enhances soil carbon sequestration, and stabilizes yields under variable climatic conditions (Tóth et al., 2025). By combining the ecological functions of trees with strategic weed management, agroforestry strengthens both mitigation (through carbon capture) and adaptation (through resilience to drought and weed pressure) components of CSA. At the landscape level, integrating agroforestry and weed management practices supports biodiversity conservation, watershed protection, and long-term productivity sustainability (Awazi et al., 2022; Zeratsion et al., 2023).

Thus, agroforestry represents a holistic weed suppression strategy that aligns ecological integrity with agricultural productivity, ensuring that weed management contributes positively to climate adaptation and mitigation goals within sustainable farming systems.

6. Climate-Smart Weed Management in Aquaculture Systems

Weeds in aquaculture systems particularly aquatic macrophytes, algae, and invasive hydrophytes pose serious challenges to water quality, oxygen balance, and nutrient dynamics. Uncontrolled aquatic weed proliferation, such as *Eichhornia crassipes* (water hyacinth), *Salvinia molesta*, and *Ceratophyllum demersum*, can lead to eutrophication, clogging of canals, fish habitat degradation, and reduced productivity (Mahmoud et al., 2021). As climate change drives temperature fluctuations, erratic rainfall, and altered hydrological regimes, the growth rate and geographic distribution of aquatic weeds are expanding rapidly (Dahal et al., 2025). Therefore, effective weed management within aquaculture must now align with Climate-Smart Agriculture (CSA) principles that promote environmental resilience, ecosystem health, and sustainable yield.

6.1 Climate-Smart Strategies for Aquatic Weed Control

1. **Integrated Aquatic Weed Management (IAWM):** Climate-smart aquatic weed management involves an integration of biological, mechanical, and ecological controls. Biological approaches such as the use of grass carp (*Ctenopharyngodon idella*), tilapia, and native weevils (*Neochetina spp.*) effectively regulate weed biomass without chemical contamination (Ullah, 2025). Mechanical harvesting and dredging, when optimized with solar-powered or low-emission machinery, minimize carbon footprints and energy use, aligning with climate mitigation goals.
2. **Eco-engineering and Habitat Design:** Designing aquaculture ponds and reservoirs to reduce weed colonization is a proactive CSA strategy. Techniques such as riparian buffer planting, controlled shading with floating solar panels, and water level regulation can suppress light-dependent weed proliferation while enhancing carbon sequestration (Gümrükçüoğlu Yiğit & Akçadağ, 2024). Constructed wetlands using fast-growing species like *Vetiveria zizanioides* and *Typha angustifolia* can absorb excess nutrients, preventing eutrophication that favors weed growth (Byekwaso et al., 2025).
3. **Nutrient and Water Management:** Excess nutrient loading from agricultural runoff accelerates algal blooms and aquatic weed invasion. Climate-smart nutrient management practices such as precision feeding, use of biofilters, and organic aquafeeds help maintain ecological balance while reducing greenhouse gas emissions from aquaculture systems (Madjar et al., 2024).
4. **Digital and Remote Sensing Technologies:** Modern tools such as satellite imaging, UAV-based monitoring, and AI-driven predictive modeling enable early detection of weed infestations and guide timely interventions. These technologies contribute to adaptive management and long-term sustainability by linking weed control to water temperature, nutrient load, and seasonal climate variability (Vijayakumar et al., 2025).

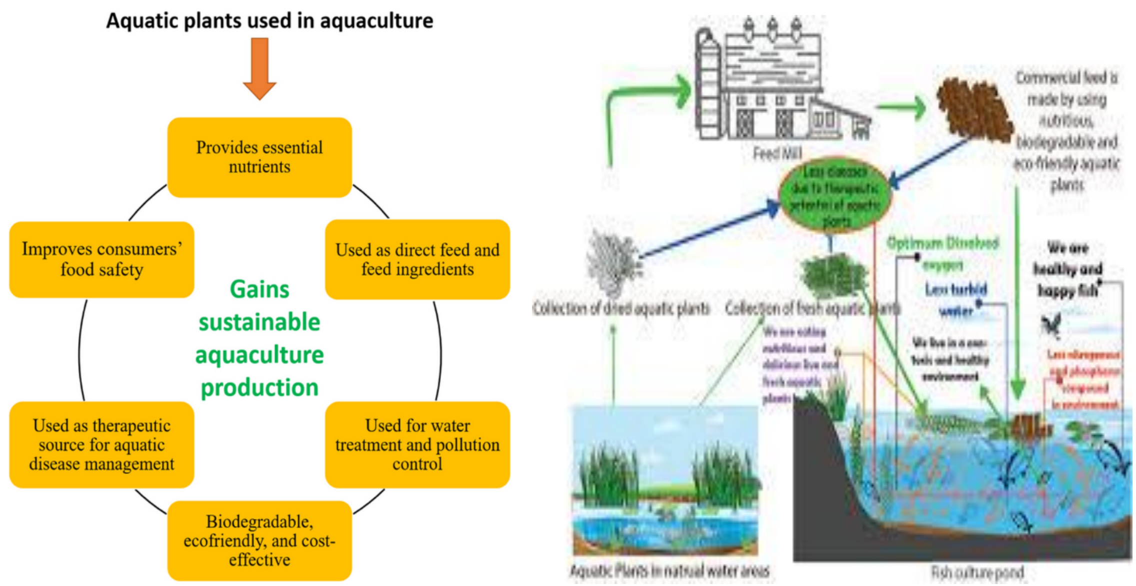


Fig 1: Benefits of aquatic plants used in aquaculture

6.2 Co-benefits and Climate-Smart Outcomes

Implementing these strategies not only curbs weed-related productivity losses but also delivers co-benefits for climate resilience. Reduced herbicide use minimizes contamination of aquatic ecosystems, while biological and mechanical methods maintain biodiversity and natural pest regulation. Furthermore, integrated aquatic weed management supports carbon sequestration through sediment stabilization, improved water quality, and enhanced vegetative biomass turnover (Walker et al., 2023; Raza et al., 2025). At the broader system level, aligning aquaculture weed management with CSA principles enhances adaptive capacity, lowers emission intensity, and promotes sustainable livelihoods among small-scale farmers (Ogwu & Kosoe, 2025). This holistic approach positions aquaculture as a key contributor to both food security and climate adaptation within the integrated landscape of Climate-Smart Agriculture.

7. Socio-Economic and Policy Dimensions

Climate-smart weed management is not only a biophysical necessity but also a socio-economic and policy-driven imperative. Its successful implementation depends on economic feasibility, social inclusiveness, institutional support, and coherent policy frameworks. For Climate-Smart Agriculture (CSA) principles to achieve large-scale impact, weed management strategies must generate tangible economic returns, be practical for smallholders, and align with national and regional climate adaptation policies.

7.1 Economic Viability and Farm-Level Profitability

Adoption of climate-smart weed management practices such as precision planting, conservation tillage, and integrated weed management (IWM) has been shown to improve input efficiency and profitability under resource-constrained conditions. By reducing herbicide dependency and energy-intensive tillage, farmers lower production costs while maintaining or increasing yields (Shah et al., 2023). For instance, precision seeding and drilling techniques improve stand establishment and reduce weed competition, translating into higher net returns and benefit-cost ratios (BCRs) compared to conventional methods (Otieno et al., 2023; Shittu & Lamarana, 2024).

Additionally, ecological methods like cover cropping and mulching enhance soil fertility and moisture retention, providing long-term economic benefits that offset initial labor investments (Sadiq et al., 2025). However, the transition to CSA-compatible weed management requires upfront investments in knowledge, technology, and labor. Therefore, access to microcredit schemes, mechanization subsidies, and cooperative-based machinery sharing can enhance economic feasibility for smallholders and women farmers, who often face capital constraints.

7.2 Social Inclusion and Capacity Building

Social dimensions particularly farmer knowledge, gender participation, and youth engagement are essential to ensure sustainable adoption of CSA practices. Studies indicate that training, farmer field schools, and participatory extension approaches increase understanding and confidence in integrated weed management systems, leading to wider adoption (Saran et al., 2024). Women, who play key roles in manual weeding and crop management, should be specifically targeted through gender-responsive training programs to ensure equitable participation and benefit sharing (FAO, 2022). Youth inclusion is equally vital: engaging young people in digital agriculture, drone mapping, and precision technologies for weed detection can enhance employment opportunities and innovation in rural areas (Aliu, 2024). Thus, human capacity development forms a cornerstone of climate-smart weed management, bridging scientific innovation with on-farm realities.

7.3 Policy Support and Institutional Frameworks

A supportive policy environment is crucial for scaling climate-smart weed management practices. Policies that promote integrated pest management (IPM), climate adaptation financing, and sustainable mechanization can accelerate CSA adoption. Governments should facilitate extension networks, public–private partnerships (PPPs), and incentives for farmers adopting low-emission technologies such as precision planters, solar-powered sprayers, and mechanical weeders (Bouri et al., 2023; Saran et al., 2024).

Moreover, integrating weed management into Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs) would ensure alignment with global climate goals and attract climate finance. Strengthening research–policy linkages through multi-stakeholder platforms can foster innovation and evidence-based decision-making (UNFCCC, 2024, WHO, 2024).

Policies that promote data-driven decision support systems linking weather forecasts, weed ecology models, and early-warning systems will further enhance adaptive capacity in the face of climate variability.

Such frameworks can help ensure that climate-smart weed management becomes an integral component of climate-resilient food systems at national and regional levels.

8. Way Forward, Case Studies, and Policy Recommendations

Climate-smart weed management (CSWM) should be embedded within national climate adaptation and agricultural development frameworks, particularly in developing economies where climate variability intensifies weed pressure and threatens smallholder livelihoods. Addressing these challenges requires linking farm-level innovation with institutional support and enabling policies.

Governments should integrate CSWM into adaptation plans, food security strategies, and sustainable intensification programs. Investment in research on climate–weed interactions, invasive species, and herbicide resistance is essential. Strengthened extension systems through farmer field schools, digital advisory platforms, and participatory research can accelerate adoption of integrated, conservation-based practices.

Economic instruments are critical to reduce adoption barriers. Transitioning to reduced tillage, residue retention, and cover cropping may involve short-term costs or risk. Targeted subsidies, access to credit, crop insurance, and results-based incentives encourage uptake. Regulatory frameworks promoting herbicide stewardship and diversified control strategies help limit resistance and environmental harm.

Real-world examples illustrate the effectiveness of CSWM across diverse systems:

Region /System	CSWM Practice	Key Outcomes	References
South Asia – Wheat–Rice Systems	Conservation agriculture, zero/reduced tillage, residue retention	Reduced weed pressure by 30-40%, improved soil moisture, increased yields under climate stress	Jat et al., 2021; Farooq et al., 2024.
East Africa – Lake Victoria Aquaculture	Community-based invasive weed management, mechanical removal, biological control (weevils), nutrient management	Improved water quality, restored fish productivity, reduced spread of aquatic weeds	Aura et al., 2022; Khotsa et al., 2025
India – Agroforestry Systems	Multilayered tree–crop combinations	Natural suppression of understory weeds, enhanced soil fertility, increased carbon sequestration, reduced chemical control need	Ghale et al., 2022; Sannagoudar et al., 2023

Because many weeds spread beyond individual farms, community and landscape-level coordination is essential. Joint surveillance, early warning systems, and collaborative management of invasive species enhance regional resilience. Integrating CSWM into watershed management, irrigation schemes, and agroforestry strengthens ecosystem regulation and reduces reinfestation.

Policies should also promote access to climate-informed decision-support tools, remote sensing technologies, and open data systems to optimize timing and precision of interventions. Public-private partnerships can facilitate technology dissemination while ensuring affordability and equity.

In sum, effective CSWM requires coordinated action across farm, community, and national levels. Aligning ecological practices with institutional capacity and supportive policies is key to reducing weed-induced losses, enhancing ecosystem stability, and ensuring climate-resilient food production.

8. Way Forward, Case Studies, and Policy Recommendations

Climate-smart weed management across agriculture, aquaculture, and agroforestry systems is central to achieving sustainable food production and climate resilience in developing economies. Integrating ecological, technological, and institutional innovations offers a transformative pathway toward reducing weed-induced losses while enhancing ecosystem stability. To ensure widespread adoption and lasting impact, strategic actions are required at multiple levels farm, community, institutional, and policy.

8.1 Strengthening Research and Innovation

Future weed management research should prioritize climate-resilient, low-emission, and biodiversity-friendly strategies tailored to local agroecological conditions. This includes:

- Developing weed-competitive and climate-resilient crop varieties,
- Expanding research on allelopathic crops and bioherbicides,
- Designing decision-support systems (DSS) that combine remote sensing, artificial intelligence (AI), and predictive climate models for early weed detection and adaptive control (Zhang et al., 2024; Yousaf et al., 2022).

Interdisciplinary collaboration among agronomists, ecologists, and data scientists is crucial for optimizing resource use efficiency and enhancing adaptive capacity. Establishing regional centers of excellence for climate-smart weed management can further promote innovation, knowledge transfer, and South–South cooperation.

8.2 Building Farmer Capacity and Knowledge Networks

Adoption of CSA-compatible weed management practices depends heavily on farmers' access to information, skills, and networks. Governments, NGOs, and international organizations should strengthen extension systems, farmer field schools, and demonstration hubs to promote integrated weed management, precision agriculture, and ecological practices (FAO, 2022; Negera et al., 2022). Community-based learning platforms, particularly those involving youth and women, can encourage technology adoption, innovation, and equitable participation. Integrating indigenous knowledge with modern CSA technologies will ensure that solutions remain locally relevant, culturally appropriate, and socially inclusive.

8.3 Policy and Institutional Reforms

National agricultural policies must explicitly recognize weed management as both a climate adaptation and mitigation strategy. Governments should integrate climate-smart weed management into National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) to attract climate finance and technical support (World Bank, 2023).

Key policy actions include:

- Providing carbon credit incentives for reduced tillage and bio-based weed management,
- Subsidizing mechanical and precision weeding tools, and

- Offering low-interest green loans for CSA-aligned equipment.

Institutional reforms should enhance coordination between agriculture, environment, and water agencies to ensure cohesive climate responses (OECD, 2024). Stronger public–private partnerships (PPPs) can accelerate innovation, bioherbicide development, and sustainable input supply chains across crop–aquaculture–agroforestry systems.

8.4 Promoting Integrated Landscape Management

Siloed interventions in crop, tree, and aquatic systems often overlook the ecological interdependencies influencing weed dynamics. An integrated landscape management approach can harmonize weed suppression across systems. This involves:

- Agroforestry for shade-induced weed control and organic litter addition,
- Aquaculture–agriculture integration for nutrient cycling and weed residue reuse, and
- Conservation tillage and cover cropping for soil cover and biodiversity enhancement (Semere et al., 2022; Sharma et al., 2025).

At the landscape scale, GIS and remote-sensing-based monitoring can guide adaptive management, improving both ecological outcomes and economic efficiency.

8.5 Financing Climate-Smart Weed Management

Access to finance remains a critical constraint for smallholder adoption. Establishing climate-smart credit lines, results-based payments, and index insurance schemes can help de-risk adoption (Kassam et al., 2022). Development banks and private investors should embed weed management within green finance and climate adaptation portfolios, ensuring steady funding for innovation, research, and extension. Participation in carbon markets can further reward practices that enhance soil carbon and reduce herbicide-related emissions.

8.6 Monitoring, Evaluation, and Impact Assessment

Robust monitoring and evaluation (M&E) systems are essential for tracking progress and ensuring accountability. Indicators should measure productivity, profitability, greenhouse gas mitigation, biodiversity outcomes, and social inclusion. Digital monitoring systems such as mobile apps, remote sensing, and satellite analytics can support data-driven decision-making (Nyamekye et al., 2024). Regular impact assessments will help refine interventions, ensuring scalability and sustainability.

8.7 Case Studies and Global Perspectives

Evidence from across Africa, Asia, and Latin America demonstrates that climate-smart weed management significantly enhances productivity and ecosystem resilience.

- In rice–wheat systems of South Asia, CSA practices such as residue retention and precision weeding reduced overall weed biomass by up to 45%, improving soil structure and yield stability (Kaur et al., 2024).
- In West African soybean systems, the integration of drilling methods and improved TGX varieties enhanced canopy closure and weed suppression while increasing net profits by over 30% (Abubakar et al., 2025).

- Latin American agroforestry models combining shade trees with maize and legume intercrops reduced aggressive grass weed species while sequestering carbon and improving soil fertility (Yiridomoh, 2025).

These examples highlight the potential of climate-smart and integrated weed management to achieve both economic and ecological resilience across agroecosystems.

8.8 Concluding Outlook and Policy Implications

The transition toward climate-smart weed management (CSWM) requires a holistic, multi-level approach that integrates agronomic innovation, environmental stewardship, and social inclusion. By combining ecological principles with technology-driven interventions across agriculture, aquaculture, and agroforestry, CSWM can deliver multiple benefits: increasing productivity, enhancing climate adaptation, reducing greenhouse gas emissions, and promoting ecosystem resilience.

Policy and institutional actions are essential to operationalize this vision. Governments must embed CSWM into national climate adaptation, sustainable agriculture, and food security policies. Clear regulatory frameworks, financial incentives, and inclusion in extension programs will enable widespread adoption and ensure alignment with broader sustainability goals. International collaborations can further support technology transfer, investment in climate-smart practices, and co-creation of context-specific solutions.

Research priorities should focus on system-level approaches that integrate weed dynamics with climate resilience strategies. This includes understanding weed–crop–environment interactions, modeling weed responses under future climatic scenarios, and evaluating ecological and socio-economic trade-offs of different management practices. Evidence generated through participatory research can guide adaptive interventions tailored to smallholder farmers' needs.

Farmer and community engagement remains central. Capacity-building programs, practical training, and access to financial mechanisms such as subsidies, microcredit, or crop insurance can facilitate the adoption of conservation-oriented and integrated weed management practices. Community-based coordination particularly for mobile or invasive weeds enhances landscape-level effectiveness and long-term sustainability.

Key Takeaways / Policy Recommendations

- **Institutional Integration:** Embed CSWM in national climate, agriculture, and food security policies.
- **Financial Incentives:** Provide subsidies, microcredit, or crop insurance to encourage adoption of sustainable practices.
- **Research Focus:** Develop system-level solutions incorporating weed ecology, crop interactions, and climate resilience.
- **Technology & Knowledge Sharing:** Promote remote sensing, decision-support tools, and participatory extension programs.
- **Community Engagement:** Strengthen landscape-level coordination and farmer networks for effective management of invasive and climate-responsive weeds.
- **International Collaboration:** Facilitate technology transfer, investment, and co-creation of locally adapted solutions.

With coherent policies, adequate financing, strong knowledge networks, and active stakeholder engagement, CSWM can become a cornerstone of resilient, regenerative, and profitable food systems under changing climatic conditions.

9. Future Prospects and Research Needs

As agriculture enters an era of increasing climatic uncertainty, future research and innovation in climate-smart weed management (CSWM) must focus on precision, adaptability, and ecological integration. Emerging technologies particularly AI-driven systems, sensor-based robotics, and machine-learning weed diagnostics are revolutionizing how farmers detect, identify, and manage weeds. Real-time data from drones, multispectral imaging, and Internet of Things (IoT) networks now allow site-specific weed interventions that minimize chemical inputs while maintaining efficiency (Upadhyay et al., 2025; Wang et al., 2025).

In the near future, hybrid precision tools integrating autonomous robots, predictive modeling, and eco-simulation will enable climate-informed weed control adapting herbicide use, mechanical interventions, and crop management to dynamic environmental conditions (Jiang et al., 2025). Furthermore, genomic-assisted breeding programs are beginning to produce weed-competitive crop varieties, combining rapid canopy closure, allelopathic potential, and root system efficiency for natural weed suppression (Kaur et al., 2024; Savić et al., 2025). These traits, once integrated into major staple crops, could significantly reduce herbicide dependence and improve resilience under variable rainfall and temperature regimes.

Interdisciplinary research remains critical. Future studies must bridge weed ecology, climate modeling, and socio-economic systems to design adaptive management frameworks that align with local agroecosystems. For example, linking weed population dynamics models with downscaled climate projections can improve forecasting of weed invasions and help predict shifts in dominant species under future climates (Yousaf et al., 2022).

Additionally, there is growing need for research on:

- Bioherbicides and allelopathic microbes that offer environmentally benign alternatives to synthetic chemicals (Choudhary et al., 2023; Raza et al., 2025);
- Soil carbon–weed interactions, exploring how regenerative practices influence weed ecology and carbon sequestration potential;
- Economic modeling of CSA weed management, quantifying the trade-offs and returns of integrated systems at regional and national scales.

Ultimately, achieving scalable CSWM requires collaborative platforms linking researchers, policymakers, and farmers to co-develop context-specific solutions that meet productivity, resilience, and environmental targets.

10. Conclusion and Policy Implications

Climate-smart weed management represents a critical pillar of sustainable agricultural intensification, balancing productivity goals with ecological integrity. The results from current research and field applications consistently demonstrate that integrating ecological, mechanical, and technological strategies can substantially enhance weed suppression while building system resilience to climate stressors (FAO, 2023; Kassam et al., 2024).

Adopting Integrated Weed Management (IWM) within a Climate-Smart Agriculture (CSA) framework reduces dependence on herbicides, minimizes greenhouse gas emissions, and supports biodiversity conservation. Practices such as drilling sowing, cover cropping, precision spot spraying, and allelopathic crop rotations exemplify the multi-functional approaches necessary for climate-resilient farming.

Policy frameworks must now evolve to institutionalize these practices through:

1. Incentive structures including subsidies for CSA equipment, carbon credits for conservation tillage, and funding for bioherbicide innovation;
2. Capacity-building programs that empower smallholders through extension services, digital platforms, and participatory innovation systems;
3. Integration of weed management into climate and biodiversity policies, ensuring synergy between agricultural, environmental, and economic objectives;
4. Public–private partnerships (PPPs) to accelerate the commercialization and diffusion of precision weeding and eco-friendly technologies.

As climate challenges intensify, CSWM provides a blueprint for regenerative and adaptive agriculture. By embedding ecological principles within innovation-driven systems, nations can achieve a triple win enhanced productivity, improved resilience, and reduced emissions.

In conclusion, climate-smart weed management is not merely a technical adjustment but a paradigm shift-one that demands holistic governance, farmer participation, and continuous scientific innovation to ensure sustainable food security under changing climatic conditions.

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