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Climate resilience in integrated weed management approaches

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Abstract

Climate-smart agriculture can bring adaptation and mitigation strategies to sustain Agricultural crop production. Climate smart Agriculture contributes the climate-resilient agricultural systems by increasing soil characteristics and the efficiency of water and nutrient use and providing stable yields and reducing emissions of Green house gases. CO₂ and temperature major contributing factors for climate change, shift in rainfall pattern also pose weed management challenges and increased crop -weed competition. Integrated weed component including summer tillage, crop rotation, modified land preparation. Climate change leads to shift in weed flora and adapt those circumstances by modifying its germination rate. Integrated weed management program is monitoring the fields for signs of weed infestation. It integrates cultural practices, mechanical methods, biological control and effectively manage weed populations. This review article emphasize the climate resilience on weed management practices such as cultural, mechanical, chemical and biological that can be used to improving crop yield.

Keywords: Climate change, integrated weed management, weed flora shift, herbicide resistance, sustainable agriculture

1. Introduction

Weeds compete with crops for essential growth resources, causing yield losses ranging from 20-80% depending on species and management practices. Under changing climate regimes characterized by elevated CO₂, erratic rainfall, and temperature fluctuations weed dynamics have become more complex. Weeds generally exhibit greater adaptability than crops, making them potential beneficiaries of global warming (Rao *et al.*, 2022) ^[1]. climate-resilient integrated weed management (IWM) systems are required, emphasizing flexibility, sustainability, and ecosystem balance. “Weeds are unwanted and undesirable plants which interfere with the utilization of land and water resources and thus adversely affect human welfare” (Rao, 2000). Institutions like Indian Council Agricultural Research and TNAU have been developing adaptive weed management modules under the National Innovation Crop Resilient Agriculture project to mitigate climate-induced challenges in agriculture. Integrating indigenous farming practices, which have proven effective in building resilience, can also enhance sustainability efforts and bolster food security (Aich *et al.*, 2022). The increasing body of literature on climate change signifies a growing acknowledgment of resilience, adaptation, and sustainability as pivotal themes in agriculture, reiterating the necessity of climate-resilient practices for food security and sustainability in India (Bremer *et al.*, 2019; Baraj *et al.*, 2024) ^[2]. Climate change has emerged as one of the most significant challenges to global agriculture, influencing crop productivity, stability of food systems, and sustainability of natural resources. Rising atmospheric carbon dioxide (CO₂) concentrations, increasing temperatures, altered rainfall patterns, and the increased frequency of extreme climatic events such as droughts, floods, and heat waves are already reshaping agroecosystems worldwide (IPCC, 2014; Dash and Hunt, 2007; Khan *et al.*, 2009) ^[3, 4, 5]. In India and other climate-vulnerable regions, agricultural production systems that depend heavily on weather conditions are particularly at risk, with observed and projected yield reductions in major crops due to climate variability and extremes (Davis *et al.*, 2019; Kumar and Upadhyay, 2019) ^[6]. Among the various biotic constraints intensified by climate change,

Weeds pose a unique and often underestimated threat to agricultural productivity. Unlike crops, weeds exhibit greater genetic diversity, phenotypic plasticity, and adaptive capacity, enabling them to respond more rapidly and aggressively to changing climatic conditions (Dukes and Mooney, 1999; Sakai *et al.*, 2001)^[8, 9]. Elevated CO₂ and temperature regimes often enhance weed growth, photosynthetic efficiency, biomass accumulation, and reproductive potential, sometimes to a greater extent than crops (Awasthi *et al.*, 2018; Bajwa *et al.*, 2019; Kapoor, 2014)^[10, 11, 12]. Several studies have demonstrated that invasive and C₄ weed species, such as *Parthenium hysterophorus*, *Commelina benghalensis*, and *Cynodon dactylon*, show enhanced growth, competitiveness, and stress tolerance under elevated CO₂ and temperature scenarios compared to C₃ crops (Price *et al.*, 2009; Manea *et al.*, 2011; Mandal *et al.*, 2017)^[13, 14, 15, 16]. This differential response alters crop-weed interactions, often intensifying competition for light, nutrients, and water, thereby aggravating yield losses under climate change (Naidu and Murthy, 2014; Naidu *et al.*, 2015)^[17, 18]. Climate change also influences weed biology and ecology, including seed dormancy, germination behavior, phenology, geographic distribution, and invasiveness. Rising temperatures and altered moisture regimes can shift weed emergence patterns and expand the potential distribution of invasive and parasitic weeds into new agroecological zones (Ooi, 2012; Banerjee *et al.*, 2019; Ren *et al.*, 2020)^[19, 20, 21]. Changes in temperature and altitude further affect weed-associated insects and biocontrol agents, modifying feeding behavior and effectiveness (Allen *et al.*, 2014; Bhusal *et al.*, 2020)^[22, 23]. Such dynamic changes complicate weed management and challenge existing control strategies. Herbicide-dependent weed control systems face growing limitations under changing climatic conditions. Elevated CO₂ and temperature have been reported to reduce herbicide efficacy by altering weed morphology, cuticle thickness, absorption, translocation, and metabolic detoxification pathways (Ganie *et al.*, 2017; Fausey and Renner, 2001; Marble *et al.*, 2015)^[24, 25, 26]. Increased tolerance of certain weed species to commonly used herbicides, such as glyphosate under elevated CO₂, further undermines chemical control reliability (Manea *et al.*, 2011; Bajwa *et al.*, 2019)^[14, 11]. In addition, excessive reliance on herbicides has led to herbicide resistance, environmental contamination, non-target effects, and rising production costs, making chemical weed management alone ecologically and economically unsustainable in the long term (Bhan *et al.*, 1999; Gharde *et al.*, 2018)^[27, 28]. Integrated and adaptive weed management approaches combining cultural, mechanical, biological, ecological, and judicious chemical methods are increasingly recognized as essential for maintaining crop productivity under climate change (Dass and Bhattacharyya, 2021; Rao *et al.*, 2022; FAO, 2023)^[29, 1, 30]. Climate-resilient weed management emphasizes enhancing system diversity, improving crop competitiveness, conserving natural enemies, and aligning weed control practices with evolving climatic conditions (Kathiresan, 2014; ICAR-NICRA, 2023)^[31, 32]. Such approaches not only reduce weed pressure but also contribute to agroecosystem resilience, environmental safety, and long-term sustainability. The primary objective of this review is to synthesize existing knowledge on the impacts of climate change on agriculture with a specific focus on weed behavior and weed management. The review aims to examine the differential responses of weeds and crops to elevated CO₂, temperature, and moisture stress. Analyze how climate change alters weed

biology, competitiveness, and distribution. Assess the limitations of herbicide-dependent weed control under changing climatic conditions. Highlight the importance and potential of climate-resilient and sustainable weed management strategies, including integrated weed management practices, to improve agricultural productivity, environmental sustainability, and agroecosystem resilience.

2. Materials and Methods

Changes in weed communities in response to crop establishment methods, soil moisture conditions (wet or dry), tillage practices, and other agronomic management strategies have been widely documented (Nichols *et al.*, 2015; Ramesh, 2015)^[33, 34]. Climate change, driven primarily by increasing atmospheric concentrations of greenhouse gases such as carbon dioxide (CO₂) and methane (CH₄), has become one of the greatest ecological challenges of the 21st century (Petit *et al.*, 1999; Kang and Banga, 2013)^[35, 36]. Rising temperatures, elevated CO₂ levels, and erratic rainfall patterns are altering weed biology, distribution, and crop-weed interactions, making effective weed management increasingly challenging. Developing climate-resilient weed management strategies is therefore essential to sustain crop productivity under changing climatic conditions. Climate-resilient Integrated Weed Management (IWM) combines cultural, mechanical, biological, and judicious chemical control methods to effectively manage weed populations while reducing dependence on herbicides. Such approaches improve weed control efficiency, delay the development of herbicide resistance, enhance soil health, conserve biodiversity, reduce production costs, increase farm profitability, and strengthen the resilience and sustainability of agroecosystems. This review synthesizes published research and field-based evidence on the influence of climate change on weed dynamics and evaluates the effectiveness of climate-resilient weed management strategies. The review focuses on: Changes in weed flora under varying temperature and rainfall regimes. Differential responses of weeds and crops to climate change. Performance of integrated weed management components, including cultural, mechanical, biological, and chemical methods. Weed control efficiency and their effects on crop growth, yield, and resource-use efficiency. Findings from experimental studies, field demonstrations, and farmer participatory trials conducted in climate-vulnerable regions, with particular emphasis on Tamil Nadu and Andhra Pradesh. The review aims to provide a comprehensive understanding of climate-resilient weed management practices that can enhance agricultural productivity, improve environmental sustainability, and support long-term food security under changing climatic conditions.

2.1. Climate change and weed dynamics

Climate change, characterized by rising temperatures, elevated atmospheric carbon dioxide (CO₂) concentrations, altered rainfall patterns, and an increased frequency of extreme weather events, has profound implications for weed dynamics in agricultural ecosystems. Owing to their high phenotypic plasticity, genetic diversity, and rapid adaptive capacity, weeds often respond more favorably to changing climatic conditions than cultivated crops. These responses result in shifts in weed species composition, distribution, invasiveness, competitiveness, and life-cycle characteristics, posing significant challenges to sustainable crop production (Dukes & Mooney, 1999; Sakai *et al.*, 2001; Naidu & Murthy, 2014)^[8, 9].

^{17]}. Consequently, climate change is expected to intensify weed infestations, increase crop-weed competition, and exacerbate yield losses across major cropping systems, emphasizing the need for climate-resilient and sustainable weed management strategies (Gharde *et al.*, 2018; FAO, 2023) ^[28, 30].

2.2. Influence of Temperature on Weed Dynamics

Rising temperatures significantly influence weed germination, growth, reproduction, and geographic distribution. Temperature regulates seed dormancy release and germination by determining the cardinal temperature requirements of weed species, often favoring those with broader thermal tolerance (Hardegree, 2006; Ooi, 2012) ^[37, 19]. Elevated temperatures can accelerate weed growth, increase biomass accumulation, and enhance reproductive potential, thereby increasing crop-weed competition. Studies have reported improved growth and invasiveness of weeds such as *Parthenium hysterophorus*, *Cynodon dactylon*, and *Trianthema portulacastrum* under warmer conditions (Kapoor, 2014; Mandal *et al.*, 2017a,b) ^[12, 15, 16]. In paddy ecosystems, higher temperatures promote rapid growth and seed production of dominant weed species, intensifying competition with rice crops (Bir *et al.*, 2018) ^[38]. Temperature also influences ecological interactions between weeds, insect pests, and biological control agents, affecting the efficiency of biological weed management (Allen *et al.*, 2014; Bhusal *et al.*, 2020) ^[22, 23]. Furthermore, elevated temperatures can modify herbicide absorption, translocation, and metabolism within weed plants, potentially reducing herbicide efficacy and increasing the risk of control failures under changing climatic conditions (Fausey & Renner, 2001; Ganie *et al.*, 2017) ^[25, 24]. These findings highlight the need to develop climate-resilient weed management strategies that remain effective under rising temperature scenarios.

2.3. Influence of elevated CO₂ on weeds and crop-weed interactions

Elevated atmospheric carbon dioxide (CO₂) enhances photosynthesis, water-use efficiency, and biomass production, particularly in C₃ plant species. Many economically important weeds respond more positively to elevated CO₂ than cultivated crops, resulting in increased growth, competitiveness, and crop yield losses (Fuhrer, 2003; Prior *et al.*, 2003) ^[39, 40]. Experimental studies have shown that elevated CO₂ promotes greater plant height, leaf area, biomass accumulation, and reproductive capacity in weeds such as *Parthenium hysterophorus*, *Commelina benghalensis*, and *Cyperus rotundus* (Price *et al.*, 2009; Marble *et al.*, 2015; Bajwa *et al.*, 2019) ^[13, 26, 11]. Similarly, Awasthi *et al.* (2018) ^[10] reported that weeds gained a competitive advantage over *Vigna radiata* under elevated CO₂, leading to greater crop yield reductions due to enhanced weed vigor. Elevated CO₂ can also influence the effectiveness of herbicides by altering weed physiology, morphology, and growth patterns. Several studies have reported reduced sensitivity of certain weed species, including exotic C₄ grasses and perennial sedges, to glyphosate under elevated CO₂ conditions, making chemical weed control more challenging (Manea *et al.*, 2011; Bajwa *et al.*, 2019) ^[14, 11]. These findings indicate that increasing atmospheric CO₂ may intensify weed problems and highlight the importance of adopting climate-resilient and integrated weed management strategies to sustain agricultural productivity under future climate scenarios.

2.4. Effect of Altered Rainfall Patterns and Extreme Weather Events on Weed Dynamics

Climate change is associated with erratic rainfall patterns, prolonged droughts, floods, and an increased frequency of extreme weather events, all of which significantly influence weed population dynamics. Many weed species possess adaptive traits such as rapid germination, prolific seed production, vegetative propagation, and tolerance to environmental stresses, enabling them to survive and proliferate under adverse conditions (Bailey-Serres & Voesenek, 2008; Chauhan & Johnson, 2010) ^[41, 42]. Flooding conditions favor the establishment and spread of hydrophytic and semi-aquatic weeds such as *Cyperus rotundus* and *Echinochloa colona*, which exhibit considerable morphological and physiological plasticity under submergence (Fuentes *et al.*, 2010) ^[43]. In contrast, prolonged drought often suppresses crop growth more severely than weed growth, allowing drought-tolerant weed species to dominate and intensify crop-weed competition (Naidu *et al.*, 2015) ^[18]. Extreme climatic events also facilitate the invasion and establishment of alien weed species by disturbing natural ecosystems and creating vacant ecological niches (Barua *et al.*, 2015; Kathiresan, 2014) ^[44, 31]. Climate niche modeling studies further predict the expansion of invasive weeds such as *Mikania micrantha* and *Cuscuta chinensis* under future climate scenarios, posing significant threats to agricultural productivity and biodiversity (Banerjee *et al.*, 2019; Ren *et al.*, 2020) ^[20, 21]. These findings emphasize the importance of adopting climate-resilient and integrated weed management strategies to effectively manage weed populations under increasingly variable climatic conditions.

2.5. Climate Change and Crop-Weed Competition

Climate change alters the balance of crop-weed competition by differentially affecting physiological processes such as photosynthesis, nutrient uptake, water-use efficiency, and phenology. Compared with crops, weeds generally exhibit greater phenotypic plasticity and resource-use efficiency, enabling them to adapt more rapidly and outcompete crops under climate-induced stress conditions (Grace, 1990; Derksen *et al.*, 2002) ^[45, 46]. Elevated atmospheric CO₂ concentrations and rising temperatures accelerate weed growth, promote earlier flowering, increase biomass accumulation, and enhance seed production, thereby intensifying competition for light, water, nutrients, and space (Naidu & Murthy, 2014; Nguyen *et al.*, 2017) ^[17, 47]. At the same time, climate stress often reduces crop vigor and productivity, particularly in rainfed and resource-limited farming systems, further increasing the competitive advantage of weeds (Davis *et al.*, 2019; Khan *et al.*, 2009) ^[6, 5]. Consequently, climate change is expected to increase weed infestation, reduce crop yields, and cause greater economic losses, especially in tropical and subtropical agricultural systems where climatic variability is more pronounced (Gharde *et al.*, 2018; Rao *et al.*, 2022) ^[28, 1]. These challenges highlight the need for climate-resilient and integrated weed management strategies to maintain crop productivity and ensure sustainable agricultural production under changing climatic conditions.

3. Climate-Resilient Integrated Weed Management (IWM)

Integrated Weed Management (IWM) is a holistic and ecologically based approach that integrates cultural, mechanical, biological, chemical, and preventive weed control methods in a compatible and complementary manner to

maintain weed populations below the economic threshold level while minimizing risks to the environment, human health, and agroecosystem sustainability. Unlike conventional weed control, IWM emphasizes long-term weed suppression rather than complete weed eradication. This approach has become increasingly important under climate change, where rising temperatures, elevated atmospheric CO₂, altered rainfall patterns, and frequent extreme weather events influence weed biology, distribution, competitiveness, invasiveness, and herbicide response (Dukes & Mooney, 1999; Naidu & Murthy, 2014; Dass & Bhattacharyya, 2021; FAO, 2023) [8, 17, 29, 30].

3.1. Principles of Climate-Resilient IWM

Preventive Measures: Prevention is the first line of defense against weed infestation. The use of clean crop seeds, weed-free farmyard manure, and uncontaminated irrigation water helps prevent the introduction and spread of weeds. Restricting the movement of invasive and herbicide-resistant weed species is particularly important, as climate change favors their establishment and expansion (Sakai *et al.*, 2001; Barua *et al.*, 2015; Kathiresan, 2014) [9, 44, 31].

Understanding Weed Ecology: Effective weed management requires knowledge of weed life cycles, germination requirements, seed bank dynamics, and stress tolerance. Climate-induced changes in temperature, atmospheric CO₂, and soil moisture influence weed emergence, growth, and reproduction, making continuous monitoring of weed populations essential for timely management (Hardegree, 2006; Ooi, 2012; Chauhan & Johnson, 2010) [37, 19, 42].

Cultural Weed Management: Cultural practices such as crop rotation, timely sowing, the use of competitive crop cultivars, optimum plant density, mulching, cover cropping, and proper fertilizer placement improve crop competitiveness and naturally suppress weed growth. These practices enhance resource-use efficiency and increase crop resilience under climate stress (Derksen *et al.*, 2002; Naidu *et al.*, 2015) [46, 18].

Mechanical Weed Management: Mechanical methods, including tillage, hand weeding, hoeing, mowing, inter-cultivation, and water management in rice ecosystems, provide effective weed control when synchronized with weed growth stages and prevailing rainfall conditions.

These methods reduce reliance on herbicides and are particularly useful in integrated weed management programs (Bhan *et al.*, 1999; Fuentes *et al.*, 2010) [27, 43].

Chemical Weed Management: Herbicides should be applied only when necessary, using the recommended dose, application timing, and method. Rotating herbicides with different modes of action helps delay the development of herbicide resistance, which may become more prevalent under elevated CO₂ concentrations and rising temperatures due to changes in weed physiology and herbicide uptake (Manea *et al.*, 2011; Ganie *et al.*, 2017; Bajwa *et al.*, 2019) [14, 24, 11].

Biological Weed Management: Biological control involves the use of insects, pathogens, grazing animals, and allelopathic plant species to suppress specific weeds. The effectiveness of biological control agents is influenced by climatic conditions, particularly temperature and moisture, making climate-adapted bioagents increasingly important for sustainable weed management (Allen *et al.*, 2014; Bhusal *et al.*, 2020) [22, 23].

Weed Seed Bank Management: Long-term weed suppression depends on reducing weed seed production and depleting the soil seed bank through crop rotation, residue management, stale seedbed techniques, and timely weed removal before seed set.

These practices are essential for maintaining low weed populations under changing climatic conditions (Grace, 1990; Ooi, 2012) [45, 19].

Climate-Adaptive Weed Management: Weed management strategies should be continuously adjusted to account for rising temperatures, elevated CO₂ concentrations, drought, flooding, and extreme weather events. Climate-resilient IWM enhances weed control efficiency, reduces crop yield losses, and sustains agricultural productivity under future climate scenarios (IPCC, 2014; ICAR-NICRA, 2023; Rao *et al.*, 2022) [3, 32, 1].

Benefits of Climate-Resilient IWM: Climate-resilient Integrated Weed Management provides cost-effective and sustainable weed control while reducing dependence on herbicides. It improves crop productivity, delays herbicide resistance, conserves biodiversity, enhances soil health, and minimizes environmental pollution. By integrating multiple weed control strategies, IWM strengthens agroecosystem resilience and supports long-term agricultural sustainability in the face of climate change (Gharde *et al.*, 2018; FAO, 2023) [28, 30].

4. Role of Ecological Approaches in Climate Resilience (Weed-Agroecosystem Perspective)

Ecological approaches emphasize working with ecosystem processes rather than relying solely on external inputs to enhance the resilience of cropping systems under climate change. Based on the references you provided, the role of ecological approaches in resilience can be synthesized under the following key themes.

4.1. Ecological Resilience and Weed Dynamics under Climate Change

Climate change alters temperature, atmospheric CO₂ concentration, rainfall variability, and the frequency of extreme weather events, all of which directly influence weed biology, distribution, and competitiveness (Dukes & Mooney, 1999; IPCC, 2014) [8, 3]. Ecological approaches to weed management emphasize understanding weed population dynamics, life cycles, seed bank behavior, and adaptive traits to predict and manage shifts in weed communities under changing climatic conditions (Sakai *et al.*, 2001; Derksen *et al.*, 2002) [9, 46]. Compared with crops, weeds generally exhibit greater phenotypic plasticity and adaptive capacity, enabling them to respond more rapidly to elevated temperatures and increased CO₂ levels (Kapoor, 2014; Nguyen *et al.*, 2017) [12, 47]. Therefore, ecological resilience can be enhanced by minimizing opportunities for weed establishment through diversified cropping systems, improved crop competitiveness, and habitat management rather than relying solely on reactive weed control after infestation.

4.2. Crop-Weed Competition and Functional Diversity

Elevated CO₂ and temperature frequently favor C₃ weeds and invasive species, intensifying crop-weed competition (Awasthi *et al.*, 2018; Price *et al.*, 2009) [10, 13]. Ecological approaches aim to enhance crop competitive ability through:

- Competitive cultivars
- Optimal plant density and spatial arrangement
- Crop diversification and rotations

Trait-based competition theory highlights that traits such as early vigor, canopy architecture, and resource-use efficiency determine competitive outcomes (Grace, 1990; Naidu & Murthy, 2014) [45, 17].

4.3. Role of Biodiversity in Ecological Weed Management

Biodiversity enhances the stability and resilience of agricultural ecosystems and increases their resistance to weed invasion (Sakai *et al.*, 2001) ^[9]. Ecological weed management promotes diversified farming practices that naturally suppress weed populations and reduce their longterm persistence. Key strategies include crop rotation to disrupt weed life cycles, the use of cover crops and smother crops to suppress weeds through shading and allelopathic effects, and landscape-level diversification to limit the establishment and spread of invasive weed species. These practices reduce the soil weed seed bank, improve soil health, enhance ecosystem resilience, and buffer the impacts of climatic variability, thereby contributing to sustainable and climate-resilient weed management (Ooi, 2012; Dass & Bhattacharyya, 2021) ^[19, 29].

4.4. Biological Control in Climate-Resilient Ecological Systems

Climate-resilient ecological systems incorporate biological control agents to regulate invasive and problematic weed species while reducing reliance on chemical herbicides. However, climate change, particularly rising temperatures and elevated atmospheric CO₂, can influence the survival, thermal tolerance, feeding behavior, and effectiveness of biological control organisms (Allen *et al.*, 2014; Bhusal *et al.*, 2020) ^[22, 23]. Therefore, successful ecological weed management requires selecting biological control agents that are well adapted to future climatic conditions, conserving natural enemies through habitat management, and understanding multitrophic interactions among weeds, crops, and biological control organisms under elevated CO₂ environments (Casteel *et al.*, 2012) ^[48]. These approaches enhance the long-term sustainability and resilience of weed management in changing climates.

4.5. Managing Flooding and Moisture Stress through Ecological Weed Management

Flooding, drought, and moisture stress significantly influence weed composition, distribution, and competitiveness in agricultural ecosystems (Bailey-Serres & Voesenek, 2008; Fuentes *et al.*, 2010) ^[41, 43]. Climate-resilient ecological weed management focuses on adapting cropping systems to changing hydrological conditions by selecting crop varieties tolerant to flooding or drought, managing weed species with adaptive traits to moisture stress, and adjusting sowing dates and cropping patterns according to seasonal rainfall variability. These practices improve crop competitiveness, reduce weed dominance during climatic extremes, and enhance the resilience and sustainability of agroecosystems under changing climate conditions (Chauhan & Johnson, 2010; Bir *et al.*, 2018) ^[42, 38].

4.6. Reducing Herbicide Dependence through Ecological Weed Management

Elevated atmospheric CO₂ concentrations and rising temperatures can reduce herbicide efficacy by altering weed growth, physiology, and herbicide absorption, thereby increasing weed tolerance and the risk of herbicide resistance (Manea *et al.*, 2011; Ganie *et al.*, 2017; Bajwa *et al.*, 2019) ^[14, 24, 11]. Ecological weed management addresses these challenges by integrating cultural, mechanical, biological, and preventive control methods rather than relying solely on chemical herbicides. This integrated approach helps delay the evolution of herbicide resistance, reduces herbicide dependence, and

promotes long-term, system-level weed suppression. Such strategies are consistent with the principles of Climate-Smart Agriculture (CSA), which emphasize sustainable crop production, environmental protection, and resilient agricultural systems under changing climatic conditions (FAO, 2023; ICAR-NICRA, 2023) ^[30, 32].

4.7. Managing Invasive Weeds under Climate Change

Climate change facilitates the spread and establishment of invasive weed species by altering temperature, rainfall patterns, and habitat suitability, allowing weeds to expand into new geographic regions (Beaumont *et al.*, 2009; Banerjee *et al.*, 2019) ^[49, 20]. Climate-resilient ecological management focuses on the early detection and prevention of invasive weeds, maintaining ecosystem integrity through diversified and healthy agroecosystems, and using climate-based distribution models to predict future weed spread and enable proactive management. These strategies are particularly important for controlling invasive alien weeds under Indian agroecological conditions, where climate variability is expected to accelerate weed invasion and threaten agricultural productivity and biodiversity (Kathiresan, 2014; Barua *et al.*, 2015) ^[31, 44].

4.8. Ecological Approaches for Long-Term Sustainability

Ecological weed management supports long-term agricultural sustainability by integrating weed control with soil health improvement, biodiversity conservation, and climate adaptation strategies (Rao *et al.*, 2022; Sahoo *et al.*, 2025) ^[1, 50]. By enhancing ecosystem resilience, reducing dependence on chemical inputs, and promoting efficient use of natural resources, these approaches contribute to sustainable crop production under changing climatic conditions. Furthermore, ecological weed management aligns with national and international initiatives on climate-resilient agriculture, supporting the objectives of Climate-Smart Agriculture (CSA) to enhance productivity, strengthen adaptation, and reduce environmental impacts (Khan *et al.*, 2009; FAO, 2023) ^[5, 30].

5. Components of Integrated weed Management under climate change

5.1. Cultural Weed Management Practices

Cultural weed management involves modifying crop and field management practices to suppress weed emergence, growth, and reproduction while enhancing crop competitiveness. Crop rotation with species differing in growth habits, planting dates, and resource requirements disrupts weed life cycles, reduces weed adaptation, and minimizes the buildup of the soil weed seed bank (Naidu & Murthy, 2014) ^[17]. The use of fast-growing cover crops and smother crops suppresses weeds through shading, competition for resources, and, in some cases, allelopathic effects, thereby reducing weed establishment and growth (FAO, 2023) ^[30]. Mulching with organic residues or synthetic materials effectively suppresses weed emergence by limiting light penetration, conserving soil moisture, and moderating soil temperature fluctuations (Dass & Bhattacharyya, 2021) ^[29]. In addition, optimizing sowing time, plant spacing, and crop density enhances crop competitiveness, allowing crops to utilize available light, water, and nutrients more efficiently than weeds (Bhusal *et al.*, 2020) ^[23]. The selection of crop varieties with rapid canopy closure, vigorous early growth, and allelopathic properties further contributes to natural weed suppression, making cultural practices an essential

component of climate-resilient and integrated weed management systems (Naidu *et al.*, 2015) ^[18].

5.2. Mechanical Weed Management Practices

Mechanical weed management involves the physical removal or destruction of weeds and is often integrated with cultural practices to achieve effective and sustainable weed control. Tillage and intercultivation reduce weed seed density, destroy emerging weeds, and improve crop establishment. Their effectiveness largely depends on the timing of operations, particularly under variable soil moisture conditions associated with climate change (Rana & Rana, 2016) ^[51]. Manual weeding remains one of the most effective methods of weed control, especially in smallholder farming systems, although it is labor-intensive and may increase production costs. The stale seedbed technique, which involves pre-sowing irrigation to stimulate weed seed germination followed by shallow tillage or non-selective weed removal before crop planting, effectively reduces early-season weed competition and the soil weed seed bank (Derksen *et al.*, 2002) ^[46]. Cropping systems such as sole cropping and intercropping also contribute to mechanical and ecological weed suppression by improving crop canopy cover, enhancing resource utilization, and reducing opportunities for weed establishment and spread (Grace, 1990) ^[45]. When combined with other integrated weed management practices, mechanical methods provide an environmentally friendly approach that reduces reliance on herbicides and improves the resilience of cropping systems under changing climatic conditions.

5.3. Chemical Weed Management Practices

Chemical weed management remains an important component of integrated weed management; however, its effectiveness is increasingly challenged by climate change. Rising temperatures, altered soil moisture, and extreme weather conditions can influence herbicide absorption, translocation, metabolism, and overall efficacy, resulting in inconsistent weed control (Fausey & Renner, 2001; Ganie *et al.*, 2017) ^[25, 24]. In addition, elevated atmospheric CO₂ can stimulate weed growth and biomass accumulation, reducing herbicide sensitivity and making certain weed species more difficult to control (Manea *et al.*, 2011; Bajwa *et al.*, 2019) ^[14, 11]. To improve long-term weed management and delay the development of herbicide resistance, herbicides should be used judiciously and integrated with cultural, mechanical, and biological weed control practices. Such an integrated approach reduces selection pressure on weed populations, enhances weed control efficiency, minimizes environmental impacts, and supports sustainable crop production under changing climatic conditions (Naidu *et al.*, 2015) ^[18].

5.4. Biological Weed Management Practices

Biological weed management is gaining importance as a sustainable and climate-resilient approach to weed control. It involves the use of natural enemies, including insects,

pathogens, and beneficial microorganisms, to suppress invasive and problematic weed species while reducing dependence on chemical herbicides. Biological control agents such as *Cyrtobagous salviniae* for *Salvinia molesta* and *Zygogramma bicolorata* for *Parthenium hysterophorus* have demonstrated considerable success in managing invasive weeds (Allen *et al.*, 2014; Bhusal *et al.*, 2020) ^[22, 23]. Allelopathic crops also contribute to biological weed management by releasing natural compounds that inhibit weed seed germination and growth. In addition, beneficial microbial antagonists can suppress weed establishment and help reduce the soil weed seed bank, supporting long-term weed management (Ritik & Dahiya, 2024) ^[52]. The effectiveness of biological weed management is strongly influenced by climatic conditions. Temperature, rainfall, and humidity affect the survival, reproduction, and feeding efficiency of biological control agents, making it essential to select climate-adapted bioagents for sustainable weed suppression under changing environmental conditions (Bhusal *et al.*, 2020; Nguyen *et al.*, 2017) ^[23, 47].

5.5. Precision and Digital Weed Management

Technological tools allow site-specific, adaptive weed control:

- Remote Sensing & AI: Detection and mapping of weed hotspots for targeted management (FAO, 2023) ^[30].
- Site-Specific Herbicide Application: Reduces chemical load and cost, increases efficiency under variable climatic conditions.
- Decision Support Systems (DSS): Integrates weather, soil, and crop models to optimize weed control timing (Prior *et al.*, 2003) ^[40].
- Herbicide Resistance Management: Digital tools help track resistant populations for adaptive management (Rao *et al.*, 2022) ^[1].

5.6. Performance of IWM Components

Table 1: Performance of Integrated weed Management (Ritik Balihar *et al.*, 2024) ^[52]

Management Approach	Key Practices	Climate resilient Adaptation
Preventive	Clean seed use, field sanitation	Reduced initial weed population by 30%
Cultural	Crop rotation, mulching, early sowing	Improved canopy coverage and suppressed late-emerging weeds
Mechanical	Rotary weeding, power weeders	Effective under intermittent drought; reduced herbicide needs
Biological	<i>Zygogramma bicolorata</i> for <i>Parthenium</i>	Maintained weed control with minimal cost
Chemical	Sequential herbicide use	Climate-adapted scheduling improved control efficiency by 25%

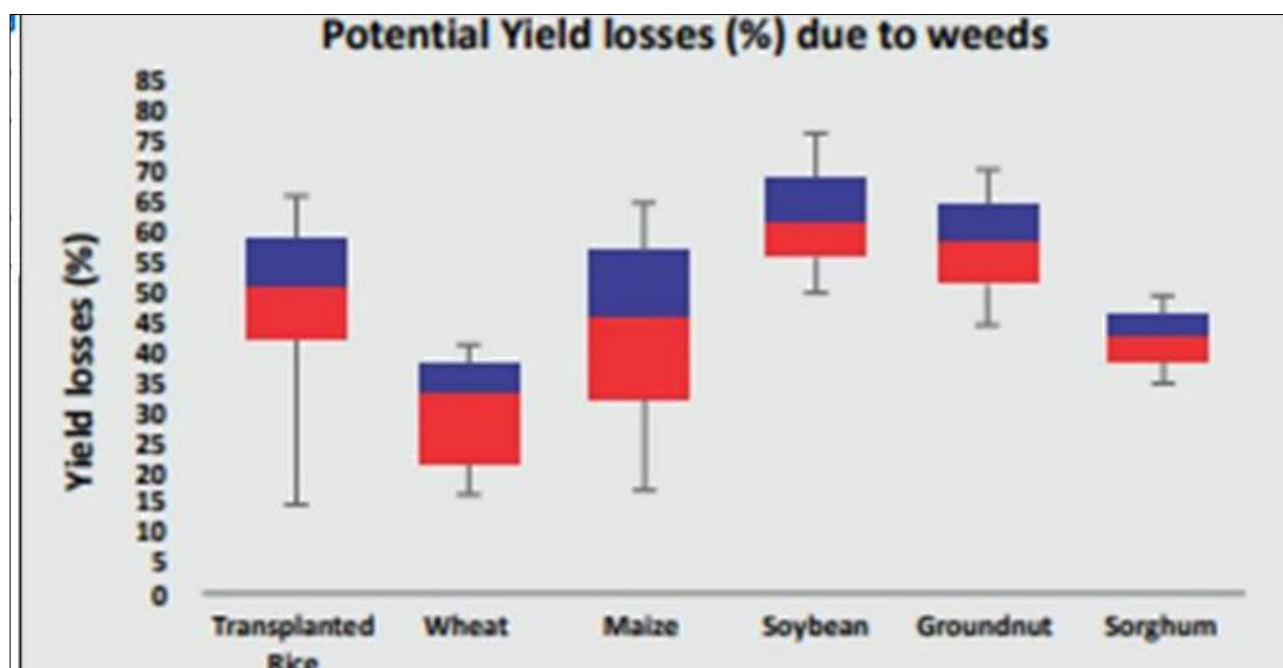


Fig 1: Potential yield losses due to weeds (Ritik Balihar et al.,2024)^[52]

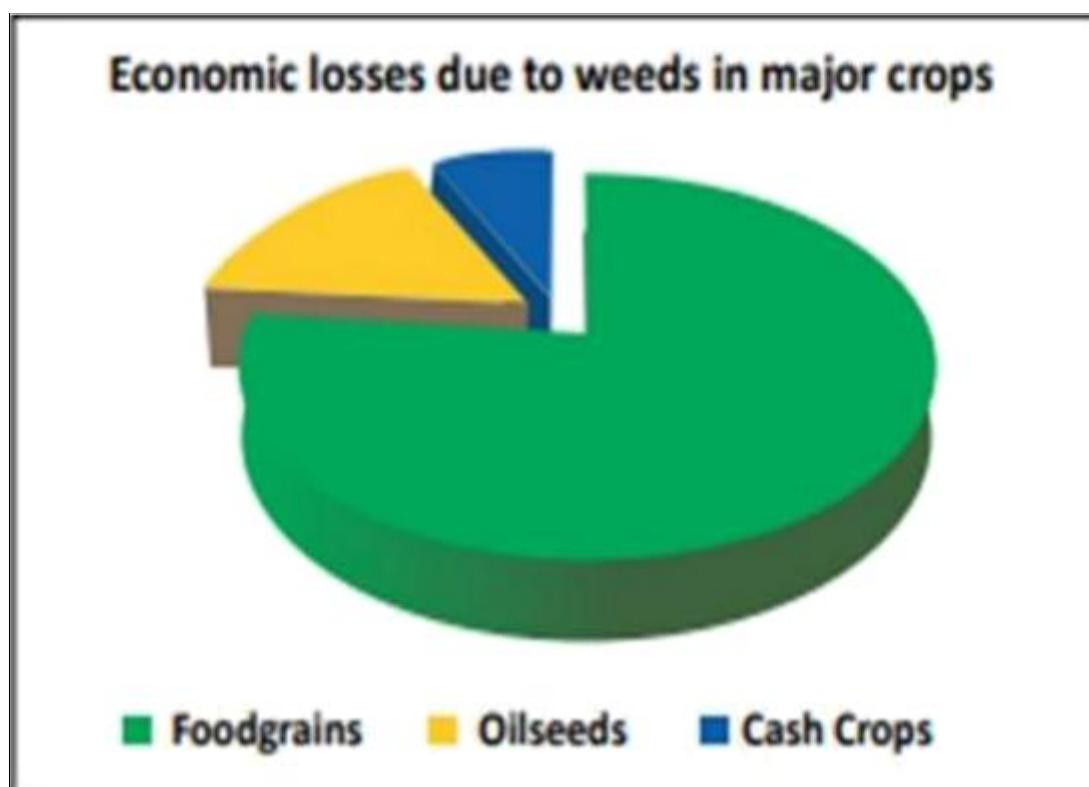


Fig 2: Economic Losses due to wes (Ritik Balihar et al.,2024)^[52]

5.7. Herbicide Resistance under Climate Change.

Climate change has emerged as a major driver of changes in weed ecology, biology, and management, with rising atmospheric CO₂, increasing temperatures, altered rainfall patterns, and frequent extreme weather events reshaping crop-weed interactions. Compared with crops, many weed species exhibit greater phenotypic plasticity, broader ecological adaptability, and faster evolutionary responses, enabling them to gain a competitive advantage under changing climatic

conditions (Dukes & Mooney, 1999; Sakai *et al.*, 2001) ^[8, 9]. Consequently, climate change is expected to increase weed infestations, intensify crop-weed competition, and reduce agricultural productivity. Under these circumstances, reliance on herbicides alone is becoming less effective because climate-induced changes in weed growth and physiology can reduce herbicide efficacy and accelerate the development of herbicide resistance. Therefore, Integrated Weed Management (IWM), which combines cultural, mechanical, biological, and judicious chemical control methods, offers the most effective and

sustainable approach for weed management under changing climates (Bhan *et al.*, 1999; Dass & Bhattacharyya, 2021; FAO, 2023) [27, 29, 30]. Future weed management should emphasize climate-resilient, ecologically based strategies that improve crop competitiveness, conserve biodiversity, maintain soil health, and reduce dependence on chemical herbicides. The integration of precision agriculture, climate forecasting, remote sensing, and decision-support tools with IWM will further strengthen weed management under variable climatic conditions. Adopting these sustainable approaches will enhance agricultural resilience, ensure long-term crop productivity, and contribute to food security in the face of global climate change.

5.8. Climate Change and Herbicide Resistance

Climate change is expected to accelerate the evolution and spread of herbicide-resistant weed populations through several interacting mechanisms. Rising temperatures and elevated atmospheric CO₂ concentrations enhance weed growth, reproductive capacity, and seed production, increasing weed population sizes and the likelihood of resistance development. In addition, climate-induced changes in herbicide performance may lead to repeated herbicide applications and greater selection pressure, accelerating the evolution of resistant weed biotypes. Climate change also facilitates the spread of invasive and herbicide-resistant weeds into new agroecological regions, posing significant challenges to sustainable crop production (Beaumont *et al.*, 2009; Nguyen *et al.*, 2017) [49, 47]. Experimental studies have shown that elevated atmospheric CO₂ can increase tolerance to glyphosate in several weed species, including *Parthenium hysterophorus* and certain *C₄* grasses, thereby reducing herbicide effectiveness (Manea *et al.*, 2011; Bajwa *et al.*, 2019) [14, 11]. Furthermore, high temperatures influence herbicide absorption, translocation, metabolism, and detoxification within weed plants, affecting herbicide efficacy and the expression of resistance mechanisms (Ganie *et al.*, 2017) [24]. These findings highlight the need for integrated and climate-resilient weed management strategies that reduce reliance on herbicides and delay the evolution of herbicide resistance.

5.9. Integrated Weed Management for Mitigating Herbicide Resistance

Integrated Weed Management (IWM) plays a vital role in mitigating herbicide resistance by integrating cultural, mechanical, biological, and judicious chemical control methods to reduce weed populations through multiple modes of action. Unlike herbicide-dependent systems, IWM minimizes continuous selection pressure on weed populations, thereby slowing the evolution and spread of herbicide-resistant biotypes. By combining diverse weed control practices, IWM enhances weed suppression, improves crop competitiveness, and increases the resilience of farming systems under uncertain climatic conditions. Evidence from India and other parts of the world indicates that diversified weed management systems are more stable, environmentally sustainable, and economically viable under climate variability than herbicide-centric approaches. Such integrated strategies reduce dependence on chemical herbicides, delay resistance development, improve soil health and biodiversity, and support long-term agricultural productivity, making IWM a key component of climate-resilient and sustainable agriculture (Gharde *et al.*, 2018; Dass & Bhattacharyya, 2021) [28, 29].

6. Climate Change Impact on Weed Ecology

Weed flora shifted towards *C₄* and drought-tolerant species like *Cyperus rotundus*, *Echinochloa colona*, and *Parthenium hysterophorus*. Elevated CO₂ favoured rapid growth and seed production in *Amaranthus viridis* and *Chenopodium album*. Herbicide degradation rates increased under high temperatures, reducing efficacy of glyphosate and pendimethalin by 15- 20% (TNAU, 2023)

6.1. Climate-Resilient Modules

1. Maize based system (Coimbatore)

Residue mulching + pendimethalin (PE) + mechanical weeding → 82% weed control, 25% higher grain yield.

2. Groundnut system (Anantapur):

Intercropping with cowpea + hand weeding → reduced weed density by 65% under deficit rainfall.

6.2. Rice system (Nagapattinam):

Alternate wetting and drying + bispyribac sodium + cono weeder → reduced methane emission and weed biomass simultaneously

6.3. Role of Precision and Information Communication Tools

Emerging technologies such as AI-based weed sensors, drones for site-specific herbicide application, and climate forecasting models enhance weed management efficiency and reduce environmental footprint (FAO, 2023) [30]. AI-driven decision support systems utilize climate analytics, soil condition insights, and crop performance data to improve decision-making processes (Jung *et al.*, 2021).

6.4. Crop - weed interactions under altering climate

Weeds are the plants which coevolved along with crops, continuously competing with domesticated plants for common resources and making the cultivation difficult. The crop yield was reduced due to weed competition by 31.5% in India and yield loss will differ because of varying competitive ability of weeds and crops (Bhan *et al.*, 1999) [27]. In another study, Gharde *et al.*, (2018) [28] reported that potential yield loss was very high in case of soybean (50-76%) followed by groundnut where 45-71% yield loss was recorded due to weeds.

6.5. Effect on weed flora shift and weed seed bank dynamics

Climate change leads to shift in weed flora as weeds can survive in diverse conditions and adapt to those circumstances by modifying its germination rate or morphological features. Weed shift is the change in the relative frequencies of weeds in a weed population or community in response to natural or human-made environmental changes in an agricultural system (Rana *et al.*, 2016) [51]. It is composed of many species, with a few dominant species comprising 70 to 90% of the total seedbank, a second group comprising 10 to 20% of the seedbank and the final group includes a small percentage of the total seed and includes recalcitrant seeds from previous seedbanks, newly introduced species and seeds of the previous crop (Wilson *et al.*, 1985) [53].

6.6. Effect on weed management

Current weed management practices have helped farmers to achieve reduction in weed population. Approaches like diversification of cropping systems, mulching and conservation tillage have added additional benefit for controlling weeds. Consequently, weed communities have changed and, in some cases, become resistant to commonly used herbicides, thus

increasing the complexity of managing weeds (Derksen *et al.* 2002)^[46]. Climate change has several consequences on weed management especially for biological and chemical control. Temperature can directly affect herbicide performance through its effects on the rate of herbicide diffusion, viscosity of cuticle waxes and physicochemical properties of spray solutions. Due to high temperature, viscosity decreases and diffusion of herbicide molecules inside the leaf tissue increases (Fausey and Renner, 2001; Varanasi *et al.*, 2016)^[25]. The response of weeds to different herbicide doses also depends on species under varied temperature levels.

6.7. Response to increased temperature, CO₂ and altered precipitation

Migration of weeds will result in a differential structure and composition of weed communities within natural and managed ecosystems due to temperature change. Thermophile weeds are the major groups most favoured by temperature. Spread of tropical and subtropical weeds into temperate areas and to increase the numbers of many temperate weeds currently limited by the low temperature at high latitudes. Example - *Parthenium hysterophorus*. For parthenium, the no. of branches (8/plant) and capitula (288/plant) produced per plant were more in summer when compared to winter (5/plant and 239/plant, respectively) (Kapoor, 2014)^[12]. This study is supported by Toh *et al.*, (2011) and reported that increased temperature enhances the growth of parthenium, enlarges canopy size and structure and accelerates population growth rate because of the shortened life cycle. Several weed species have adopted mechanisms like avoidance, escape or quiescence strategy to survive flood induced stress.

6.8. Case Studies and Regional Experiences

Parthenium weed in India: Elevated CO₂ and temperature increased biomass and glyphosate tolerance; integration of bioagents and chemical control improved suppression (Bajwa *et al.*, 2019; Bhusal *et al.*, 2020)^[11, 23]. Rice fields with C4 weeds: Growth under elevated temperature and CO₂ showed higher competitiveness; mechanical removal plus herbicide rotation mitigated impacts (Bir *et al.*, 2018)^[38]. *Mikania micrantha* in Australia: Climate modelling predicted range expansion; integrated management including biocontrol reduced invasion risk (Banerjee *et al.*, 2019)^[20].

7. Challenges in Implementing Climate-Resilient Integrated Weed Management

Despite its advantages, the implementation of climate-resilient Integrated Weed Management (IWM) faces several challenges. Climate variability alters the timing and effectiveness of cultural, mechanical, biological, and chemical weed control methods, making weed management more complex and less predictable. In many regions, the adoption of IWM is constrained by limited farmer awareness, inadequate technical knowledge, labor shortages, and financial and resource limitations. The increasing occurrence of herbicide-resistant weed populations under changing climatic conditions further complicates weed management, reducing the long-term effectiveness of chemical control methods (Manea *et al.*, 2011)^[14]. Moreover, integrating multiple weed management practices across diverse cropping systems, agroecological zones, and farming conditions requires location-specific knowledge, continuous monitoring, and adaptive management strategies (Naidu & Murthy, 2014)^[17]. Addressing these challenges

through research, farmer training, policy support, and the development of climate-resilient weed management technologies is essential for achieving sustainable agricultural production.

8. Future Research Directions and Recommendations

Future research should focus on predicting shifts in weed distribution and invasion under different climate change scenarios using ecological and climate niche models to support proactive weed management (Ren *et al.*, 2020)^[21]. Greater emphasis should be placed on understanding crop-weed interactions under combined climate stresses, including elevated atmospheric CO₂, rising temperatures, drought, flooding, and erratic rainfall, to develop climate-resilient weed management strategies. The promotion of Climate-Smart Agriculture (CSA) should be strengthened through the development of region-specific Integrated Weed Management (IWM) guidelines, financial incentives, and policy support for sustainable weed management practices. Capacity-building programs are also essential to train farmers in adaptive IWM strategies, precision agriculture technologies, remote sensing, digital decision-support tools, and climate-based advisory services. Future research should also prioritize climate-induced herbicide resistance, the development of climate-adapted biological control agents, breeding of crops with enhanced allelopathic and competitive traits, and the integration of precision weed management technologies with IWM. These innovations will improve weed control efficiency, reduce environmental impacts, strengthen agroecosystem resilience, and ensure sustainable crop production under changing climatic conditions (Sahoo *et al.*, 2025)^[50].

9. Conclusion

Climate change is significantly altering weed ecology, distribution, and crop-weed interactions through rising temperatures, elevated atmospheric CO₂ concentrations, changing rainfall patterns, and increasing frequency of extreme weather events. Compared with crops, weeds generally possess greater phenotypic plasticity, genetic diversity, and adaptive capacity, enabling them to respond more rapidly to changing climatic conditions. As a result, weed infestations, crop-weed competition, and yield losses are expected to increase, posing a major challenge to sustainable agricultural production. Conventional herbicide-based weed management alone is becoming less effective because climate change influences herbicide efficacy and accelerates the evolution of herbicide-resistant weed populations. Therefore, Integrated Weed Management (IWM), which combines cultural, mechanical, biological, and judicious chemical control methods, provides a more sustainable and climate-resilient approach to weed management. Ecological strategies such as crop diversification, cover cropping, biological control, conservation of biodiversity, and precision weed management further enhance the resilience of agricultural systems while reducing environmental impacts. Future efforts should focus on developing climate-smart weed management technologies, strengthening farmer awareness and capacity building, promoting policy support for sustainable weed management, and integrating precision agriculture with climate forecasting tools. Continued research on weed ecology, herbicide resistance, biological control, and crop-weed interactions under changing climatic conditions will be essential for improving the effectiveness of climate-resilient weed management. Adopting these integrated and sustainable

approaches will enhance agricultural productivity, conserve natural resources, and contribute to long-term food security in the face of climate change.

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