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REVIEW ARTICLE

Effect of increasing atmospheric CO_2 and temperature on weeds and their management - Mitigation strategies

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ABSTRACT

Agriculture is highly vulnerable to climate change, which influences key factors like land, water, and environmental conditions critical for crop production. Rising atmospheric CO_2 and global temperatures exacerbate these challenges, particularly by enhancing the growth and competitive advantage of certain weed species. Elevated CO_2 levels stimulate photosynthesis and biomass accumulation in C_3 weeds, allowing them to outcompete crops, while higher temperatures shift weed growth cycles and distributions. Together, these changes complicate weed management, reduce herbicide efficacy, and contribute to resistance development. The combination of environmental stressors, such as heat and water scarcity, further strains agricultural systems, threatening food security and economic stability. This review critically examines the impacts of ever-increasing CO_2 and temperature on weed biology, physiology, and population dynamics. It highlights the consequences of weed shifts, invasions, and altered life cycles, emphasizing the challenges these pose to agricultural systems. Drawing on recent findings, including experimental data from Open Top Chambers (OTCs) and Free Air CO_2 Enrichment (FACE), the review discusses how elevated CO_2 and elevated temperature can impact weed management practices. It also proposes mitigation strategies aimed at addressing these challenges, including the development of climate-resilient weed management practices and integrated weed management approaches. Understanding the impacts of climate change on weed dynamics is crucial for designing sustainable agricultural systems capable of adapting to future environmental conditions.

Keywords: Climate change, Crop-weed interaction, Elevated CO_2 and Elevated temperature, Weed physiology, C_3 plants and C_4 plants

INTRODUCTION

Agriculture is particularly vulnerable to climate variations, as it heavily depends on land, water, and other natural resources that are directly influenced by changing environmental conditions (Walsh *et al.* 2020, Gowda *et al.* 2018). In addition to nutrient and field management, crop production is strongly influenced by the cumulative effects of soil, water, and weather conditions throughout the growing season (Nolte *et al.* 2018). Frequent and severe droughts, in particular, negatively affect plant growth, physiology, and reproduction, leading to significant reductions in crop yields (Barnabas *et al.* 2008, Satoh *et al.* 2020, Yordanov *et al.* 2020, Pokhrel *et al.* 2021). These yield reductions not only threaten global food security but also exacerbate economic volatility in agriculture, with fluctuations in crop prices and trade restrictions impacting farmers' livelihoods.

Global average temperatures have been consistently reaching new records, accompanied by increasingly unreliable rainfall patterns and extreme weather events such as droughts, floods, and storms, all of which are intensifying the stress on agricultural systems (Global Climate Report, 2022). The risks of heat and water stress are expected to escalate, posing further challenges to crop production (USGCRP 2017). Furthermore, climate change is contributing to the wider spread of pests, weeds, and diseases, which are causing severe crop failures across various regions (Ziska *et al.* 2016, EPA 2022). As these climatic shifts continue, agricultural productivity is expected to become more variable, with some regions experiencing improvements while others suffer devastating losses (Wu *et al.* 2015, Liang *et al.* 2017, Ortiz-Bobea *et al.* 2021, Liang 2022).

Among the numerous threats posed by climate change, the proliferation of weeds under elevated CO_2 and temperature conditions presents a critical

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challenge for sustainable agriculture. Rising atmospheric CO_2 levels enhance photosynthesis in certain weed species, particularly C_3 weeds, leading to greater biomass and competitive ability against crops. Simultaneously, higher temperatures may shift weed growth cycles, phenology, and geographical distributions, complicating management efforts. Consequently, the effectiveness of herbicides, which are already under pressure due to resistance development, is further compromised under these altered environmental conditions. This review explores the impact of ever-increasing atmospheric CO_2 and temperature on weeds and their management, while highlighting potential mitigation strategies aimed at maintaining agricultural productivity in the face of a changing climate.

Climate change: Rising atmospheric CO_2 and temperature

The 2023 IPCC Synthesis Report underscores the mounting challenges of climate change, warning of a high likelihood that global temperatures could exceed 1.5°C between 2021 and 2040, particularly under high-emission scenarios (Bacchin *et al.* 2023). By 2023, human-induced warming had already reached 1.31°C, driven by record levels of greenhouse gas emissions (Forster *et al.* 2024). The report highlights the disproportionate effects of climate change on vulnerable populations and stresses the urgency of taking substantial, immediate action to reduce emissions. If these efforts are not undertaken, the consequences could be dire, with current climate commitments falling short and potentially leading to a 3.2°C rise in global temperatures if current trends continue (Bongaarts 2024). While adaptation strategies, particularly in urban systems, are viewed as critical, many argue that adaptation alone will not suffice and that broader systemic changes are required to build resilience (Bacchin *et al.* 2023).

One of the key contributors to rising global temperatures is the increase in atmospheric CO_2, which has surged by approximately 40% since the late 19^{th} century, contributing to a 1.07°C increase in global temperatures (Adak *et al.* 2023). Projections suggest that, without significant mitigation efforts, CO_2 levels could rise to two to four times higher than those seen in the past 800,000 years, leading to unprecedented climatic changes (Raviraja 2023). The IPCC warns that if emissions remain unchecked, global temperatures could rise by 3.6 to 4.4°C by the end of the century (Adak *et al.* 2023), with severe implications for biodiversity and food security. Agricultural systems, in particular, are at risk, as rising temperatures and CO_2 levels are expected to exacerbate the severity of diseases such as rice sheath blight, further threatening food production (Shen *et al.* 2023). Continued reliance on fossil fuels could significantly increase CO_2 emissions, further destabilizing global climate systems (Raviraja 2023). While natural climate variability is also debated as a factor influencing temperature trends, the overwhelming consensus emphasizes the need for robust mitigation strategies to prevent the most severe consequences of climate change (Edmonds 2023). Without decisive action, the future of ecosystems and human societies faces unparalleled risks.

Effect of rising levels of CO_2 and temperature on plants in general

The rising concentrations of atmospheric greenhouse gases, particularly CO_2, have accelerated global warming and increased the frequency of climate extremes in recent decades (Sage 2020, Zandalinas *et al.* 2021). These extreme climate events, including temperature extremes and erratic patterns of precipitation, have had profound impacts on global agricultural systems, leading to reductions in crop growth and yield (Fahad *et al.* 2017). Concurrently, the ongoing decline in arable land and increasing population pressures have raised concerns about global food insecurity (Borrelli *et al.* 2020, Sage, 2020; Zandalinas *et al.* 2021). With global food demand expected to rise significantly in the coming decades (Conijn *et al.* 2018), the sustainability of crop production under changing environmental conditions has become a central challenge for agriculture.

Cereals, which are essential for human food and livestock feed (McKenzie and Williams 2015, Bruinsma 2017), are particularly vulnerable to these environmental changes. The ability of different cereal species and varieties to withstand such stress is strongly influenced by their genetic makeup, as well as by physiological and molecular mechanisms that contribute to stress tolerance (Raza *et al.* 2019). To adapt to the rapidly shifting climate, one promising strategy is the alteration of cropping systems to favor species with specific traits, such as adjusting the proportion of C_3 and C_4 plants based on their differing responses to environmental conditions (Rezaei *et al.* 2023). Additionally, crop management practices and the development of crops with enhanced resistance to environmental stresses are critical for ensuring resilient food systems. While the mechanisms governing crop responses to individual stressors are relatively well understood, the effects of multiple, simultaneous environmental factors on crop performance—particularly under conditions where stress responses interact synergistically or antagonistically—remain poorly understood (Zandalinas and Mittler 2022). Crop modeling has emerged as a valuable tool for predicting the future impacts of climate change on cereal production and for evaluating the differential responses of C_3 and C_4 crops to environmental stress (Wang *et al.* 2023).

Drought stress, for instance, can significantly reduce photosynthesis, nutrient uptake, and overall biomass production, leading to lower grain yields. In response, plants activate a range of physiological and molecular mechanisms, such as stomatal closure, osmolyte and antioxidant accumulation, and modifications in root architecture (Farooq *et al.* 2009, Anjum *et al.* 2011, Zhao *et al.* 2020). Elevated CO_2 concentrations, on the other hand, can improve photosynthesis and water use efficiency, potentially boosting biomass and yield under favorable conditions (Leakey *et al.* 2019, Souza *et al.* 2019). Moreover, CO_2 enrichment has been shown to mitigate the adverse effects of water scarcity to some extent (Abdelhakim *et al.* 2022). However, increased leaf area under elevated CO_2 could counterbalance these benefits by amplifying transpiration, thereby exacerbating the effects of drought (Burkart *et al.* 2011). Studies have also reported a reduction in herbicide efficacy under drought stress conditions (Sreekanth *et al.* 2024b)

High temperatures also pose a significant threat to cereal crops, particularly during reproductive stages, by disrupting key physiological processes like photosynthesis, respiration, and stress signaling pathways (Tiwari and Yadav 2019). While plants employ protective mechanisms such as heat shock proteins, antioxidant production, and alterations in membrane fluidity to combat heat stress (Jat *et al.* 2016), prolonged exposure to extreme heat can cause irreversible tissue damage and, in some cases, plant death. Addressing the combined challenges of drought and heat stress, especially in the context of rising atmospheric CO_2, will require a deeper understanding of how these factors interact to influence crop productivity.

Effect of rising levels of CO_2 and temperature on weeds in particular

Rising atmospheric carbon dioxide and temperature can alter the growth and physiology of weedy plants. A few of the weed species may become inactive, while the rest may become aggressive invaders. Certain weed species possess the ability to survive and establish under changed climate by means of different dispersal and adaptive mechanisms (Bergmann *et al.* 2010) and try to persist after they have become established (Smith *et al.* 2011).

Weed shift and invasion

Weeds which are not adapted to the changing climate tend to shift to more favorable conditions. Native weeds that are favored by changes in carbon dioxide, temperatures and rainfall will tend to become invasive by intensifying its population and range. *Lantana camara*, for example, could expand its range if rainfall increased in some areas. Alien invasive weeds, which have strong reproductive potential, are reportedly get benefited from climate change. Introduced weeds can contribute to significant economic losses in agriculture and impose a substantial financial burden on resources allocated for the management of natural areas (Sreekanth *et al.* 2022). Therefore, it is predicted that alien weeds, such as parthenium (*Parthenium hysterophorus* L.) and chromolaena (*Chromolaena odorata* (L.), will be more aggressive under raised CO_2 level (Chandrasena 2009, Naidu 2013). Overall, increasing CO_2 and temperature may alter dominant weed species and increase weed problems (Ziska and Dukes 2011).

Weed growth and biology: Increasing atmospheric CO_2 has been shown to stimulate growth and development in several weed species. CO_2 can affect plant and leaf size, seed size and production, the nutritive value of leaves to herbivores, plant toxicity and pollen production. Due to changing climate, changes in timing of life-cycles are expected that will affect flowering, fruiting and reproduction as the flowering is the most thermal sensitive stage of plant growth (Boote *et al.* 2005). From the experiments conducted in Open Top Chambers (OTCs) at ICAR-Directorate of Weed Research, Jabalpur, India, it was observed that CO_2 enrichment (550 ppm) hastened the seed maturity in *Avena fatua* (Wild oat), a common weed in wheat and the seeds matured two weeks in advance compared to that of seeds from the plants grown under ambient CO_2 (380 ppm) conditions (Naidu 2011).

Crop-weed Interactions: Coexisting crop and weed plants primarily have competitive interactions. Changes in climatic factors such as increasing CO_2, temperature and precipitation can potentially influence crop-weed competition. Weeds pose significant challenges under changing climate conditions, severely impacting crop productivity and agricultural systems, particularly in major crops such as rice (Sreekanth *et al.* 2023a, Mahawar *et al.* 2023, Roy *et al.* 2023, Sreekanth *et al.* 2024a, Pawar *et al.* 2022), wheat (Sondhia *et al.* 2023), soybean

(Chander *et al.* 2023), and potato (Chethan *et al.* 2023). The rising CO_2 and temperature will affect the crop-wed competition (Ziska 2022), which varies with the nature of weeds and crops (Chongtham *et al.* 2019, Ziska *et al.* 2019). It is likely that rising CO_2, coupled with high temperature conditions will benefit weeds more than crops (Holt *et al.* 2013)

a. Effect of elevated CO_2 on crop-weed interaction: Increasing atmospheric CO_2 concentrations have been shown to significantly enhance the growth and development of numerous plant species (Poorter 1993, Sage 1995). The plant response to elevated CO_2 varies based on their photosynthetic pathways (C_3 or C_4). However, predicting the effects of elevated CO_2 on crop-weed interactions in controlled environments often leads to insufficient quantification of competition, as field conditions rarely involve single-weed infestations (Ziska & Goins 2006). Limited studies have explored the response of crops and weeds in competitive settings under elevated CO_2 (Ziska 2004, Ziska & Goins 2006), highlighting the need for more research involving weed-crop mixtures. In general, C_3 crops (e.g., rice, wheat, soybean) tend to benefit more from elevated CO_2 due to higher photosynthetic rates compared to C_4 weeds like Palmer amaranth (*A. palmeri*), waterhemp (*Amaranthus rudis*), and kochia (*K. scoparia*) (Elmore & Paul, 1983). For C_3 crops such as rice and wheat, elevated CO_2 can improve competitiveness against C_4 weeds (Yin & Struik 2008, Fuhrer 2003). However, studies have shown that under drought conditions and elevated CO_2, *Phalaris minor*, a C_3 weed, was more competitive than wheat (Naidu & Varshney 2011). The impact of elevated CO_2 on weedy and cultivated rice was also studied in open-top chambers, revealing positive effects on leaf area, tiller number, photosynthetic rate, and transpiration in both rice types (DWR 2013-14, Sreekanth *et al.* 2023b).

b. Impact of elevated temperature on crop-weed interaction: At elevated temperatures, plants with the C_4 photosynthesis pathway, primarily weeds, tend to have a competitive edge over crops that use the more common C_3 pathway (Yin and Struik 2008). A temperature increase of 3°C, for instance, significantly boosts the growth of itch grass (*Rottboellia cochinchinensis*), a highly competitive C_4 weed in key cropping systems like sugarcane, corn, cotton, soybean, grain sorghum, and rice. This weed is predicted to spread further into regions like the central Midwest and California (Patterson *et al.* 1999). C_4 species, such as *Amaranthus retroflexus* and *Sorghum halepense*, are expected to fix CO_2 more efficiently than C_3 crops like soybean and cotton, especially during midday when both light intensity and temperature peak. Due to their high water use efficiency and CO_2 compensation point, C_4 plants are better suited to cope with increased evaporative demand in high temperatures (Bunce 1983).

c. Interactive effect of elevated CO_2 and temperature on crop-weed interaction: Several studies conducted at ICAR-DWR have shown that *Phalaris minor* gains a competitive advantage over wheat under elevated temperature alone, or when combined with elevated CO_2. Similarly, other research revealed that the combination of elevated temperature and CO_2 delays panicle maturity in cultivated rice, weedy rice, and wild rice (DWR 2014-15, DWR 2015-16). In competitive interactions, elevated CO_2, elevated temperature, and their combination favored *Euphorbia geniculata* (C_3) over greengram and C_4 weeds like *Amaranthus viridis* (DWR 2016-17). Elevated temperature, whether alone or combined with CO_2, had a negative impact on wheat, while *Phalaris minor* was unaffected (DWR 2015-16). These findings suggest that under future climate change scenarios (elevated CO_2 and temperature), *Euphorbia geniculata* may outcompete both greengram and *Amaranthus viridis* (DWR 2016-17).

Climate change and weed management

Climate change poses several challenges for managing weeds. Climate change may have more implications on weed management in different crops and cropping systems owing to differential growth response of crops and weeds.

Manual and mechanical weed management: Elevated CO_2 commonly stimulates below ground growth and this may make manual weeding a difficult task as CO_2 rises. High temperatures create drier conditions which makes manual or even mechanical removal of weeds harder. Efficiency of farm labor vis-a-vis manual weeding would get negatively affected due to temperature rise and also harder surface soil.

Chemical weed management: It is imperative to manage the weeds to reduce the crop losses and it is generally done through a number of control strategies including manual, mechanical, biological and chemical methods depending on various factors such as cropping systems, environment, resources *etc*. However, chemical methods are favored because of uniformity and ease of application, high efficacy, cost effectiveness and time saving (McErlich and Boydston 2013). Over the past two decades, the use of herbicides for weed control has increased in India because of its effectiveness in improving e crop yields and saving labour and energy. However, the effectiveness of a given herbicide relies not only on its chemical properties but also on its interaction with the plant and the environment. Besides morphological and anatomical characters of the target plant, environmental conditions play a crucial role in determining the efficacy of herbicides at the time of application. Several environmental factors such as temperature, solar radiation, humidity etc., and interaction among them influence physiological processes of a plant and its susceptibility to herbicide. Changes in the global climate due to a rise in atmospheric CO_2 and associated increase in temperature can have significant impacts on plant growth and herbicide performance. Therefore, understanding the effects of rising CO_2, temperature and other environmental factors on weed growth and herbicide efficacy is important to optimize the herbicide application for effective weed control. Climate change factors, besides positive effect on weed growth, could affect the efficacy of many herbicides, making weed management a difficult task for sustainable crop production. A number of studies indicate that rising atmospheric CO_2 is likely to alter or negatively influence the performance of herbicides (Manea *et al.* 2011, Sreekanth *et al.* 2023). Higher temperatures could increase both absorption and translocation of foliar applied herbicides adding to efficacy, but also increase volatility and microbial breakdown (Atienza *et al.* 2001).

Research findings evidently show that rising CO_2 can significantly reduce protein levels in plant tissues (Taub *et al.*, 2008). Less protein would result in less demand for aromatic and branched chain amino acids, with a potential decline in the efficacy of herbicides (e.g. Glufosinate, Glyphosate) that act as enzyme inhibitors (Varanasi *et al.* 2016). Absorption and translocation of foliar applied herbicides varies with orientation and surface area of the leaf. If leaf number or area is stimulated due to rising CO_2 or temperature, then such changes would increase herbicide interception and absorption during spraying. Temperature alters relative humidity and the main effect of relative humidity is in controlling the speed at which a spray drop dries on the leaf surface. There is good evidence that penetration slows down and may cease when the drop dries out. Low relative humidity causes the drop to dry out faster thus herbicide activity is usually lesser. High relative humidity favors opening of the plant stomata, low relative humidity may lead to stomatal closure. Allometric changes (variable growth in different plant parts) can affect herbicide interactions. For example, altered root shoot ratio in Parthenium exposed to elevated CO_2 (Naidu 2013).

It is increasingly evident from the research findings that changing climate conditions may reduce the sensitivity (increase the tolerance) of weeds to some herbicides. Matzrafi *et al.* (2019) reported that glyphosate-treated plants (*Conyza Canadensis* and *Chenopodium album*) grown under increased temperature and elevated CO_2 level exhibit reduced glyphosate sensitivity. Thus, the continued overreliance on glyphosate for weed control under changing climatic conditions may result in more weed control failures. High CO_2 and high temperature increased the resistance level of Multiple Resistant *Ehinochloa colona* to cyhalofop-butyl (Refatti *et al.* 2019).

Bio-control of weeds: Climate change may indirectly affect bio-control of weeds by the way of its direct influence on the reproduction, survival, distribution and behavior of bio-agents especially insects (Sujayan and and Karuppaiah 2016). Feeding habits of insects may get affected due to changes in nutritional properties of weeds under high CO_2 (Casteel *et al.* 2012). Successfully adapted and established bio-agents may also get affected due to climate change. For example, feeding efficiency of *Zygogramma bicolorata* on Parthenium is reportedly decreased at the optimal temperatures above 27-30! (Kumar *et al.*, 2021). Similarly, reproduction and development of *Cyrtobagous salviniae*, a bio-control agent of *Salvinia molesta* may get affected due to rising temperature (Allen *et al.* 2014). Decreased plant palatability of Alligator weed (*Alternanthera philoxeroides*) under drought has reportedly caused reduction in population growth of its bio-agent *Agasicles hygrophila* suggesting that drought can reduce the biological control of Alligator weed indirectly by interrupting plant–insect interaction (Wei *et al.* 2015).

Mitigation strategies

Existing weed management strategies, to be effective, need specific environmental conditions that are becoming less predictable in the present scenario of changing climate. Owing to their greater adoption potential, weeds are likely to out-compete the crops under changing climate & resources. The conditions of changing climate might necessitate the adoption of new agronomic practices to enhance weed competitiveness.

Preventive measures: Seeds of most crops are contaminated with weeds, especially where weed seeds resemble the shape, size and color of crop seeds. Minimizing weed seed contamination with crop seed is the primary step in preventing the possible weed competition with emerging crop.

Cultural practices: Adjusting the sowing/planting date is one of the effective strategies to mitigate the adverse effects of climate change on crop production. Manipulating the sowing or planting time in such a way that the conditions for weed germination or emergence are not favorable. For example, early sowing of wheat by two weeks reduces the problem of *Phalaris minor* and *Avena fatua* in north-western part of the Indo-Gangetic plains because these weeds require low temperature for germination (Dinesh Jinger *et al.* 2016). Direct seeding is the preferred option for rice cultivation in the scenario of water shortage which is aggravating day by day due to global warming. However, more than 90% of the yield reduction in rice is attributed to weed competition. Experimental results of Agronomy Division, Faculty of Agriculture, SKUAST-Kashmir showed that earlier sowing of DSR (10^{th} May) was more effective than late sowing (3^{rd} June) with respect to growth characteristics, yield, weed population per unit area, dry weed biomass and economics (Mir *et al.* 2024).

Crop diversification and climate resilient crops cultivars: Competitiveness against weeds differs with crops and crop cultivars. Crop diversification and cultivation of weed smothering crops is equally important for weed management. Instead of traditionally–adopted cropping systems, inclusion of climate-resilient and weed smothering crops (i.e. millets and small millets) in a cropping system helps in minimizing the weed infestation to a great extent. Cultivars resilient to climate change conditions especially drought, flooding, high temperature can overcome the weed competition to some extent. For example, temperature-insensitive cultivars can cope up with high temperatures

Challenges ahead

Increased weed proliferation and aggressiveness: Elevated atmospheric CO_2 levels enhance the growth and reproductive potential of many weed species, particularly C_3 plants, which may outcompete crops for resources such as light, water, and nutrients. This increased weed biomass will demand more intensive management efforts, complicating weed control strategies, especially in regions already struggling with high weed infestations.

Herbicide resistance and reduced efficacy: Climate change is expected to exacerbate the ongoing issue of herbicide resistance. Rising temperatures and elevated CO_2 levels can reduce herbicide efficacy by altering weed physiology, growth stages, and herbicide absorption rates. Weeds may evolve resistance more quickly, rendering conventional chemical controls less effective and increasing the reliance on higher doses or alternative herbicides, which could raise environmental concerns.

Shifts in weed phenology and distribution: As temperatures increase and precipitation patterns change, weeds will likely shift their geographical range, leading to the invasion of new areas and crops. These shifts in weed distribution, particularly by invasive species like *Lantana camara* and *Parthenium hysterophorus*, may create new challenges for farmers unfamiliar with these weeds, further complicating their management and increasing production costs.

Complex interactions between weeds, crops, and climate extremes: The interaction between weeds, crops, and multiple environmental stressors such as drought, heatwaves, and floods complicates predictions and management strategies. These stressors may enhance the competitive advantage of certain weed species, while others might decline, creating unpredictable and site-specific weed dynamics that require localized management solutions.

Impact on biological weed control: Changes in temperature and CO_2 levels may also affect the effectiveness of biological control agents, such as insects and pathogens used to manage invasive weeds. Altered climatic conditions may impact the life cycle, efficacy, or survival of these agents, reducing their reliability as a weed management tool under climate change.

Adaptation of weeds to environmental stresses: Many weed species exhibit a high degree of adaptability, which allows them to thrive under various environmental stresses, including drought and high temperatures. This ability to rapidly adapt may enable weeds to continue proliferating even under extreme conditions, making it difficult for current management practices to keep pace with their evolving characteristics.

Resource constraints and economic costs: Addressing these growing weed management challenges will require substantial investment in research, extension services, and infrastructure. Farmers, particularly in developing regions, may face financial barriers in accessing new technologies and adopting integrated weed management practices. Additionally, rising herbicide costs and the need for more frequent applications may further strain economic resources in agricultural systems.

Knowledge gaps and uncertainty in long-term impacts: While the effects of elevated CO_2 and temperature on certain weed species are well documented, there remains considerable uncertainty about how climate change will affect the full spectrum of weed species, their interactions with crops, and their responses to management practices over time. Long-term studies are needed to fully understand these complex interactions and to develop more robust and predictive weed management models.

Development of climate-resilient management practices: The need for novel, climate-resilient weed management practices is urgent. Traditional herbicide-based approaches may not be sustainable in the face of rising resistance and reduced efficacy under climate change. There is a need to integrate cultural, mechanical, and biological control strategies with chemical management to create more holistic and adaptive weed management systems that can withstand future environmental changes.

Conclusion

The rising atmospheric CO_2 levels and increasing global temperatures are significantly altering weed biology and ecology, creating complex challenges for agricultural systems, particularly in weed management. Enhanced weed growth, shifted distribution patterns, and increased herbicide resistance require innovative and adaptive management strategies. The interplay of elevated CO_2, temperature, and other environmental stressors leads to unpredictable weed dynamics, complicating effective control methods. Conventional herbicide approaches may become less effective, highlighting the need for alternative practices such as cultural, mechanical, and biological controls. Developing resilient, climate-adaptive weed management strategies is crucial for maintaining crop productivity amid these changes. However, knowledge gaps persist regarding the long-term effects of climate change on weed species and their management, underscoring the importance of ongoing research and localized, sustainable solutions. Moving forward, a multidisciplinary approach that integrates scientific research, policy innovation, and farmer education is essential to address these emerging challenges. Stakeholders must invest in climate-resilient agricultural technologies and practices to adapt to evolving weed dynamics. A proactive and integrated strategy will be vital in mitigating the adverse effects of climate change on weed management, thereby safeguarding global food security.

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