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# Evolution of Herbicide Resistant Weeds under Changing Climate: A Threat to Food Security

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**SUMMARY**

Climate change is reshaping agricultural landscapes worldwide, intensifying the challenge of managing weeds already one of the most persistent threats to crop productivity. Rising atmospheric $CO_2$ levels, increasing temperatures, and shifting rainfall patterns are not only altering weed distribution and growth but also accelerating the evolution of herbicide-resistant weed populations. Emerging evidence shows that climate-driven changes can reduce herbicide efficacy, enhance weed metabolism, influence gene expression, and increase opportunities for gene flow between resistant and susceptible biotypes. Some resistance-conferring mutations even provide additional fitness benefits, enabling weeds to thrive in the absence of herbicide pressure. These complex interactions highlight the growing difficulty of relying solely on chemical control strategies. As climate variability strengthens selective pressures on weeds, the risk of widespread herbicide resistance increases, posing a significant threat to global food security. Understanding how climate change intersects with weed biology and resistance evolution is therefore essential for developing resilient, integrated, and sustainable weed management approaches for the future.

## INTRODUCTION

Climatic uncertainties and the increasing frequency of extreme events pose substantial environmental risks to agricultural productivity and long-term sustainability (Negi et al., 2024). Among biotic stresses, weeds remain one of the most significant constraints to global crop production (Sreekanth et al., 2023; Sreekanth et al., 2025a). Climate change particularly elevated $CO_2$ concentrations and rising temperatures can markedly alter the molecular, physiological, and biochemical responses of weedy species (Roy et al., 2023; Sreekanth et al., 2025b; Sreekanth et al., 2024). Consequently, effective weed control and management will be pivotal for ensuring food security in the face of a rapidly growing global population (Roy et al., 2022; Pawar et al., 2022; Sondhia et al., 2023; Mahawar et al., 2023). Additionally, advancing our understanding of the mechanisms that drive herbicide resistance is critical for developing innovative and sustainable weed management strategies. While the alternative approaches discussed here provide valuable directions, they represent only a small portion of the comprehensive efforts required. Continued progress in education, herbicide chemistry, and the understanding of weed biology and ecology integrated with considerations of climate variability will be indispensable for preparing the next generation of scientists and land managers to address these emerging challenges (Chander et al., 2023; Chetan et al., 2022; Sreekanth et al., 2025c).

Climatic factors such as temperature, precipitation, light intensity, relative humidity, dew, wind, and soil moisture directly and indirectly influence herbicide efficacy (Sreekanth et al., 2023). These variables not only affect herbicide penetration, absorption, and retention within plant tissues but also alter plant growth and physiological processes, thereby impacting herbicide translocation and overall performance. Additionally, environmental conditions can modulate the degree of herbicide resistance expressed in weed populations. Several studies have shown that resistance to herbicides such as paraquat (Lasat et al., 1996; Yu et al., 2009) and glyphosate (Ge et al., 2011) can shift significantly with changes in temperature. In evaluating the interplay between herbicide resistance and climate change, it is also essential to recognize the influence of pleiotropic phenotypes linked to specific resistance mutations. These phenotypes often reduce plant fitness, imposing a disadvantage relative to susceptible biotypes (Kumar et al., 2025a; Kumar et al., 2025b). Fitness penalties typically manifest as reductions in traits associated with survival and reproductive success. In weeds, such fitness-related attributes are commonly measured through seed yield, seed weight, germination capacity, and dormancy patterns (Vila-Aiub, 2019; Pasala et al., 2025). Because these traits are strongly shaped by environmental factors (Basavaraj PS et al., 2025), ongoing climate change is likely to intensify their variability, thereby influencing the evolutionary trajectories of herbicide resistance in weed populations.

Much remains unknown about the intricate interactions among rising atmospheric $CO_2$ levels, broader climate change, and weed biology, and many of these insights will only become clearer through real-world observations in the coming years. However, current evidence already indicates that elevated $CO_2$ and increasingly variable climatic conditions will impose strong selection pressures on weed species, accelerating their adaptive evolution. This trend poses major challenges for chemical weed control and, more broadly, for chemical pest management. The long-term selection effects of rising $CO_2$, coupled with differential responses between crops and weeds, add further complexity. One major concern is gene flow, particularly as shifts in phenology and flowering time under elevated $CO_2$ may promote hybridization and facilitate the transfer of herbicide-resistance traits. This has been observed in weedy red rice and Clearfield® rice, where elevated $CO_2$ resulted in overlapping flowering periods, increasing rice de-domestication and the formation of more weedy, herbicide-resistant hybrid progenies (Ziska et al., 2012). Another important aspect is $CO_2$-driven selection between herbicide-resistant and susceptible weed biotypes. For example, projected future $CO_2$ concentrations have been shown to enhance resistance in multiple-resistant junglerice (*Echinochloa colona* L.) to cyhalofop-butyl (Refatti et al., 2019). The case of Kochia further highlights that, beyond current challenges associated with herbicide resistance, the combined effects of resistance evolution and climate change are likely to intensify weed management difficulties in the future.

Herbicide efficacy is highly dependent on favourable environmental conditions (Varanasi et al., 2016). With the increasing frequency of high-temperature events projected by the Intergovernmental Panel on Climate Change (IPCC), global agriculture and particularly weed management is expected to face new and significant challenges (IPCC, 2014). Emerging research demonstrates that elevated temperatures can markedly reduce the effectiveness of several widely used herbicides. For example, reduced efficacy has been noted for cyhalofop on *Echinochloa colona* (Refatti et al., 2019) and for glyphosate on *Conyza canadensis*, *Chenopodium album* (Matzrafi et al., 2019), and *E. colona*. Likewise, Matzrafi et al. (2016) reported decreased sensitivity to ACCase inhibitors under high-temperature conditions, likely attributable to enhanced metabolic detoxification of the herbicide.

These findings underscore the critical role of genotype × environment and gene × environment interactions, particularly in shaping non-target-site resistance (NTSR) mechanisms. If rising temperatures continue to compromise the performance of foliar-applied herbicides, the consequent repeated exposure of weed populations to sublethal or “low-dose” herbicide levels could hasten the evolution of resistance. This highlights a probable crosstalk between heat stress responses and herbicide detoxification pathways in plants, reinforcing the need for integrated and adaptive weed management strategies under future climate scenarios. However, it is becoming increasingly clear that reliance on a single weed control strategy particularly herbicide-based approaches is not sustainable over the long term. The rapid emergence of herbicide-resistant weeds, including biotypes resistant to multiple modes of action, highlights the pressing need to reconsider conventional weed management practices. Several comprehensive reviews (Matzrafi et al., 2016) have stressed the importance of re-evaluating and modernizing weed control technologies, especially herbicide efficacy, in the context of the dynamic spatial and temporal patterns of weed evolution and adaptation.

Against this backdrop, the current era represents a pivotal moment for confronting the dual challenges posed by rising atmospheric $CO_2$ concentrations and increasing climate variability. Any redefined weed management paradigm must explicitly incorporate these environmental drivers, given their profound impacts on weed biology, evolutionary trajectories, and herbicide performance. Therefore, understanding and integrating the effects of elevated $CO_2$ and climate uncertainty into weed management strategies is essential for ensuring long-term agricultural sustainability and resilience (Sreekanth et al., 2024; Laxman et al., 2024). Climate change has driven notable shifts in weed flora across many arable ecosystems in recent decades (Peters et al., 2014; Naidu et al., 2024; Sondhia et al., 2024). Thermophilic, late-emerging, and opportunistic weed species are becoming increasingly common in modern cropping systems. As a result, weeds exhibiting high phenotypic plasticity and greater tolerance to extreme weather conditions are more likely to survive, persist, and eventually dominate. Although herbicide resistance mechanisms are often associated with fitness costs, certain mutations may instead confer fitness benefits, providing adaptive advantages even in the absence of herbicide selection pressure. The occurrence of herbicide-resistant (HR) weed populations in fields that have never been treated with herbicides can partly be explained by such beneficial mutations.

For example, the I1781L mutation in the ACCase gene not only imparts target-site resistance (TSR) but also enhances biomass production in Setaria italica (Wang et al., 2010) and delays seed germination in Alopecurus myosuroides (Délye et al., 2013). Delayed germination may allow this species to escape early-season weed control practices, further contributing to its persistence. Thus, certain HR biotypes may possess additional ecological advantages under specific environmental conditions, even in the absence of herbicide application. Supporting this idea, Délye et al. (2013) reported that the I1781L mutation in A. myosuroides was present at relatively high frequencies in weed populations prior to herbicide exposure indicating that it functions as an “efficient” resistance gene, one that provides resistance without imposing substantial deleterious pleiotropic effects. Global climate change has accelerated plant invasion rates (Diez et al., 2012) and altered the geographical distribution of several highly competitive weed species (Stratonovitch et al., 2012). As a result, understanding gene environment interactions has become essential for elucidating how climate change indirectly influences the evolution of herbicide resistance. Environmental factors can also directly regulate the expression of herbicide resistance (HR) genes, as shown by Vila-Aiub et al. (2013). Notably, Matzrafi et al. (2016) demonstrated that climate change can diminish herbicide efficacy by enhancing metabolic activity in weeds, thereby increasing the likelihood of non-target-site resistance (NTSR) evolution.

In this context, Markus et al. (2017) suggested that epigenetic modifications in HR plants may offer valuable insights into how environmental stresses shape resistance development. Because NTSR mechanisms often play a central role in a weed’s adaptive response to abiotic stresses (Délye, 2013), it is reasonable to hypothesize that weeds harboring such mechanisms may be better equipped to survive under climatic stressors such as elevated temperatures or altered precipitation regimes that accompany global climate change (Chander et al., 2024). If such subtle, climate-driven selection pressures are indeed at work, they may pose an even greater challenge to sustainable weed management than the well-recognized issues associated with herbicide misuse or overdependence.

## CONCLUSION

Herbicide-resistant weeds are emerging as one of the most serious and fast-evolving challenges in modern agriculture, and climate change is amplifying this threat. Elevated $CO_2$, rising temperatures, and shifting weather extremes are creating favourable conditions for weed proliferation while simultaneously undermining the effectiveness of widely used herbicides. These environmental changes accelerate weed adaptation through enhanced metabolism, altered gene expression, increased hybridization potential, and shifts in growth and phenology. In some cases, resistance mutations offer ecological advantages, enabling resistant biotypes to persist and even dominate even in the absence of herbicide use. If these trends continue unchecked, the combined forces of climate change and herbicide resistance may jeopardize global food production systems and compromise long-term food security. Addressing this challenge requires a fundamental rethinking of current weed management paradigms, moving beyond overreliance on herbicides toward integrated, diversified, and climate-smart strategies. Strengthening research on weed ecology, resistance mechanisms, climate impacts, and adaptive farm practices will be crucial. Ultimately, empowering farmers, scientists, and policymakers with this knowledge will be key to safeguarding agricultural sustainability in a rapidly changing world.

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