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Future Directions in Weed Science Research: Innovations for a Sustainable and Climate Resilient Agriculture

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SUMMARY

Climate change is reshaping agricultural ecosystems, intensifying challenges related to weed proliferation, herbicide resistance, and crop–weed competition. As global temperatures rise, CO_2 levels increase, and weather patterns become more erratic, many weed species are adapting faster than crops, threatening food security and sustainable crop production. At the same time, weeds possess extraordinary resilience tolerance to heat, drought, salinity, and flooding; rapid reproductive strategies; and high genetic plasticity that makes them not only formidable competitors but also valuable biological resources. Modern weed science is undergoing a significant transformation, shifting from conventional weed suppression toward more integrated, innovative, and science-driven approaches. Emerging tools such as genomics, gene editing, precision agriculture, AI-assisted weed detection, bioherbicides, ecological weed management, and the exploration of weed-derived stress-tolerance genes are opening new avenues for climate-resilient agriculture. This article highlights the key future directions in weed science research, emphasizing innovations that enhance sustainability, mitigate climate risks, support herbicide stewardship, and strengthen crop resilience. By leveraging technological advancements and ecological insights, weed science holds immense potential to contribute to a productive, sustainable, and climate-ready agricultural future.

INTRODUCTION

Weeds have been shaped for centuries by powerful natural and human-driven selection pressures, allowing them to thrive in environments where many crops struggle (Chethan et al., 2022; Chander et al., 2023). Their ability to withstand soil disturbances, fluctuating climate conditions, repeated drought events, and evolving cultivation systems has enabled them to develop unique adaptive traits (Chander et al., 2024; Kumar et al., 2025b; Mahawar et al., 2023). Many weed species exhibit remarkable tolerance to multiple stresses heat, salinity, drought, flooding along with highly efficient nutrient acquisition mechanisms, rapid life cycles, prolific seed production, and increasing resistance to pests, diseases, and herbicides (Kumar et al., 2025a; Sreekanth et al., 2025a; Sreekanth et al., 2024a). Their extraordinary genetic plasticity not only makes them formidable competitors in agricultural systems but also positions them as an untapped reservoir of genes that could help build the next generation of climate-resilient crops (Sreekanth et al., 2025b; Sreekanth et al., 2023; Sreekanth et al., 2024b). As climate change accelerates and agricultural challenges intensify, scientists are increasingly exploring weed genomes to discover traits and molecular mechanisms that could enhance crop survival, productivity, and sustainability under future climatic extremes (Sreekanth et al., 2025c). This emerging perspective marks a transformative shift in weed science moving beyond weed suppression toward harnessing their biological strengths to drive innovation in sustainable and climate-resilient agriculture. Given the rapid transformations in agroecosystems, it is essential to intensify and broaden research in the following domains to advance weed science and support sustainable crop production.

1. Phytohormonal signaling and cross-talk under weed stress

Weed interference triggers complex hormonal responses in crop plants, reshaping their growth, metabolism, and stress tolerance. Phytohormones such as auxins, cytokinins, ethylene, gibberellins, abscisic acid, salicylic acid, and jasmonates interact dynamically when crops face shading, nutrient depletion, and allelopathic chemicals released by weeds. Understanding this hormonal cross-talk is emerging as a major research frontier because it determines how plants perceive weed presence and initiate adaptive responses. Future studies will aim to map these hormonal networks in greater detail, identify key molecular switches that regulate shade avoidance and stress mitigation, and develop hormone-based bioregulators or genetically engineered crops that maintain productivity even under high weed pressure.

2. Transcription factors as molecular targets for enhancing stress tolerance

Transcription factors (TFs) act as powerful master regulators of gene expression during weed-induced stress. Families such as MYB, WRKY, NAC, bZIP, and AP2/ERF modulate numerous processes, including photosynthesis, oxidative stress management, nutrient uptake, and morphological plasticity. With advanced molecular tools like transcriptomics and CRISPR-based editing, TFs have become promising targets for strengthening crop resilience. Future research will focus on discovering weed-responsive TF networks, identifying TFs associated with early vigor and improved nutrient use, and manipulating these factors to create crops capable of withstanding competition without yield loss.

3. Source–sink relationships during critical competitive periods

Weeds profoundly alter source–sink relationships during early crop development, particularly in cereals like rice and wheat. When weeds dominate, photosynthesis declines as leaves receive less light, reducing carbohydrate production (source), while growing organs such as roots and developing panicles suffer from insufficient assimilate supply (sink). This imbalance ultimately limits biomass accumulation and grain yield. Future research will examine how carbon allocation shifts under weed stress, explore crop genotypes with stable source–sink ratios despite competition, and employ tools like metabolomics and carbon isotope tracing to understand how crops prioritize energy use during critical competitive periods. Such insights will help breeders design crop ideotypes with enhanced resilience and resource-use efficiency.

4. Molecular strategies for improving weed stress tolerance

Advanced molecular technologies are redefining weed science by offering innovative ways to strengthen crop tolerance. CRISPR/Cas-mediated gene editing allows precise modifications in weed-responsive genes, while RNA interference (RNAi) offers opportunities to suppress harmful pathways activated by weed stress. Additionally, metabolomics is helping identify biochemical markers associated with tolerance, and epigenomic studies are revealing heritable stress adaptations. Future molecular strategies will combine these tools to develop crops with enhanced competitive ability, reduced susceptibility to shading, and robust physiological mechanisms that maintain yield even in the presence of weeds.

5. Phytoremediation using weeds as a sustainable approach

Many weed species possess exceptional ability to accumulate heavy metals, degrade organic pollutants, or detoxify contaminated soils—a capacity known as phytoremediation. Instead of viewing such weeds solely as pests, future weed science will explore their use as ecological cleanup agents. Species like Amaranthus, Parthenium, and certain sedges could be harnessed to rehabilitate polluted farmlands, mitigate pesticide residues, and improve soil health. Upcoming research will focus on identifying hyperaccumulator species, optimizing their biomass for maximum pollutant uptake, and integrating phytoremediation with climate-smart farming systems.

6. Edible Weeds: Climate-smart genetic resources for the future

Edible weeds such as amaranth, purslane, and chenopodium are emerging as important contributors to climate-resilient food systems. These plants not only survive under harsh conditions like drought and poor soils but also provide high nutritional value, including proteins, minerals, antioxidants, and vitamins. With increasing demand for sustainable and nutrient-rich foods, research on edible weeds will expand toward their domestication, cultivation practices, nutritional profiling, and potential in food and nutraceutical industries. As climate change intensifies, edible weeds may evolve from being underappreciated wild species to mainstream components of resilient food systems.

7. Improving nutrient use efficiency in crops under weed stress

Weeds are aggressive nutrient competitors, often reducing the availability of nitrogen, phosphorus, and potassium to crops. Improving nutrient use efficiency (NUE) under weed stress is therefore a major scientific priority. Future research will focus on identifying crop genotypes with strong root systems, efficient nutrient transporters, and resilient physiological mechanisms that maintain nutrient uptake even under competition. The development of tailored fertilization strategies, smart nutrient formulations, and crop varieties with high NUE will significantly reduce the impact of weeds while lowering production costs and environmental pollution.

8. Harnessing weed genetic diversity for crop improvement

Weeds possess remarkable genetic diversity and evolutionary adaptability, often thriving under extreme environmental conditions. This makes them valuable sources of stress-tolerant traits such as heat resistance, drought tolerance, nutrient scavenging ability, and pest resilience. Future research will focus on collecting and characterizing weed germplasm, identifying stress-resilient alleles, and introgressing beneficial genes into cultivated crops through pre-breeding and advanced molecular breeding. By tapping into weed genetic resources, scientists can develop next-generation crop varieties capable of performing well under climate stress and competitive conditions.

9. Impact of weed stress on plant growth and physio-morphological traits

Weeds influence critical physiological and morphological traits such as leaf expansion, root growth, photosynthesis rate, and biomass distribution. Understanding these effects is essential for breeding competitive crops. Future research will prioritize detailed phenotyping of crops under weed stress using high-throughput imaging, sensor-based measurements, and 3D modeling to identify traits that contribute to early vigor, efficient light capture, and strong root competition. These insights will inform breeding programs aimed at creating crops that naturally suppress weeds through superior growth and architecture.

10. Regulation of primary metabolism during plant–weed interactions

Weed stress disrupts fundamental metabolic processes including carbohydrate metabolism, amino acid synthesis, lipid turnover, and energy production. This metabolic imbalance affects crop growth and yield. Future directions in research will focus on metabolic profiling to identify key pathways affected by weed competition, understanding how primary metabolism contributes to tolerance, and engineering metabolic pathways to enhance stress resilience. Integrating metabolomics with molecular biology will offer a holistic view of how plants adjust their biochemistry under competitive environments.

11. Weed Genomics: Unlocking new insights for weed and crop management

The sequencing of weed genomes is opening new avenues in weed science, enabling researchers to pinpoint genes responsible for rapid adaptation, herbicide resistance, and stress tolerance. Weed genomics will play a crucial role in predicting weed evolution, designing targeted management strategies, and identifying novel genes that can be used in crop improvement. Future research will expand genomic databases, develop comparative genomics tools, and utilize genomic selection to manage herbicide-resistant weeds more effectively.

12. Enhancing crop competitiveness using bioregulators

Bioregulators such as growth hormones, bio-stimulants, and signaling molecules can significantly enhance crop competitiveness by improving early vigor, strengthening root growth, and optimizing shoot architecture. Future research will investigate the role of bioregulators in modulating crop responses to weed stress, their interactions with nutrient uptake, and their potential to reduce herbicide dependency. Integrating bioregulators into sustainable crop management practices will offer eco-friendly solutions for improved crop performance under competitive conditions.

CONCLUSION

The future of weed science is shifting from a narrow focus on weed eradication to a broader, more integrated approach that embraces molecular innovations, ecological knowledge, and sustainable farming systems. By exploring phytohormonal networks, harnessing genetic diversity, advancing weed genomics, and utilizing weeds for phytoremediation and food resources, scientists are redefining the role of weeds in agriculture. These research directions will not only enhance crop resilience and productivity but also contribute to climate-smart, environmentally sustainable agricultural practices. Ultimately, the next era of weed science will transform weeds from agricultural adversaries into valuable partners for global food and ecological security.

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