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REVIEW ARTICLE

Wild crop relatives as genetic resources: Advanced strategies for breeding climate-resilient crops

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Abstract

With climate change threatening global food security, wild crop relatives (WCRs) have emerged as a game-changing resource for breeding crops that can withstand extreme conditions. These wild ancestors of modern crops hold the key to traits like drought tolerance, heat resistance and pest resilience that many domesticated varieties have lost over time. By tapping into the genetic diversity of WCRs, scientists can develop stronger, more adaptable crops that can thrive in challenging environments. Recent advances in plant breeding, such as marker-assisted selection (MAS), genomic selection and CRISPR gene editing, have made it easier to transfer valuable traits from WCRs into cultivated crops. However, challenges remain, including genetic incompatibilities, slow breeding processes and the need for better conservation efforts to protect these wild species. Seed banks, in-situ conservation and advanced breeding programs are helping to safeguard this genetic treasure trove for future generations. This review examines the potential of wild crop relatives (WCRs) to transform climate-resilient agriculture by showcasing advanced breeding techniques and identifying remaining challenges. Harnessing wild genes alongside modern scientific approaches offers a path toward a more sustainable and food-secure future.

Keywords: climate-resilient crops; CRISPR; food security; gene editing; genetic diversity; wild crop relatives (WCRs)

Introduction

Plant breeding is both an art and a science for shaping plants to meet human needs by enhancing their genetic traits. With the growing challenges of climate change, breeding crops that can withstand adverse conditions has become more important than ever (1). Climate change is no longer a distant threat; it's happening now, with real and immediate consequences. It refers to shifts in global climate patterns, largely driven by human activities (2). The year 2024 is on track to be the hottest in recorded history. While climate variations have always occurred naturally, human influence has accelerated these changes at an alarming rate. One of the biggest casualties of climate change is agriculture. Rising temperatures, unpredictable rainfall and extreme weather events are making it harder to grow crops (3). In hotter regions, food production is expected to decline significantly, while some colder areas may see temporary benefits (4). However, increased temperatures interfere with essential plant physiological activities, such as photosynthesis and water retention, leading to yield declines. Crops like maize, wheat and rice are particularly vulnerable, with every 1 °C temperature rise reducing wheat yield by 6 % and maize yield by 7.4 % (5). Beyond heat stress, climate change brings other challenges: water shortages, erratic weather patterns, soil degradation and the spread of new crop diseases (6, 7, 8). Together, these factors pose a significant threat to global food security, indicating that traditional crop breeding methods alone are insufficient and new strategies are necessary.

Climate change is also throwing global food supply chains off balance, causing unpredictable price swings of essential crops like wheat, rice and maize. This uncertainty hits both farmers and consumers very hard, making food security even more of a challenge (9). The World Bank warns that climate change could push more than 100 million people into extreme poverty by 2030, with farming communities being hit the hardest (10). On top of that, climate change is expected to have lasting effects on agriculture, potentially slowing down economic growth in countries that depend on this sector. For example, a study by the International Food Policy Research Institute (IFPRI) suggests that by 2050, climate change could reduce global GDP by 0.8 %, with agriculture among the hardest-hit sectors (9). And as if that weren't enough, the loss of arable land from soil degradation, desertification and rising sea levels only adds to the long-term economic struggles.

Unlocking a Hidden Resource for Climate-Resilient Crops:

A promising solution involves Crop Wild Relatives (CWRs), which are wild plant species closely related to cultivated crops. These plants have survived in diverse environments for thousands of years, naturally evolving resistance to drought, heat, pests and diseases (11). Unlike modern crop varieties, which have lost much of their genetic diversity due to selective breeding, CWRs still carry genes that could help crops adapt to climate change. WCRs are found within the same genus of cultivated crops, offering a genetic reservoir for breeding new, more resilient varieties (12). By identifying and incorporating beneficial traits from wild relatives, breeders can improve stress tolerance, disease resistance and even nutritional quality in commercial crops (13, 14). These hidden genetic resources could be the key to securing food production in a predictably unpredictable world. The contribution of Wild relatives for critical climate adaptation has been shown in Table 1. This review explores the potential of WCRs in modern plant breeding, highlighting their role in developing crops that can withstand the challenges of a changing climate. Utilizing nature's inherent solutions allows us to develop a more sustainable and resilient food system for the future.

Advanced Strategies for Breeding Climate-Resilient Crops

The increasing frequency of environmental stresses such as drought, salinity and extreme temperatures poses significant challenges to global agriculture. To mitigate these challenges, wild crop relatives (WCRs) offer a rich reservoir of adaptive traits that can be harnessed to enhance stress tolerance in cultivated crops. For instance, wild barley (*Hordeum spontaneum*), wild emmer wheat (*Triticum dicoccoides*) and various *Brachypodium* species exhibit unique stomatal and photosynthetic traits shaped by differing environmental conditions (18). WCRs also possess genes that allow them to thrive in saline and drought-prone environments. An example is *Leymus mollis*, a wild relative of wheat, which demonstrates remarkable salt tolerance and could be used to develop wheat varieties capable of thriving in soil with high salinity (19). Additionally, wild chickpea (*Cicer reticulatum*) genotypes from moderate climates exhibit greater drought and heat tolerance compared to those from extreme environments, challenging the assumption that adaptive traits are predominantly found only in adverse conditions (20).

While WCRs provide a valuable genetic pool, advancements in molecular breeding have significantly enhanced our ability to efficiently harness these traits. The revolution in plant breeding began in the 1980s with the advent of DNA molecular markers (21). These markers have transformed plant breeding by helping researchers explore genetic relationships between crops and their wild relatives, as well as by enabling the fingerprinting of different cultivars and breeding lines. Furthermore, molecular markers allow us to pinpoint the biochemical basis of traits and locate quantitative trait loci (QTLs) that contribute to trait inheritance. As a result, marker-assisted selection became possible, allowing breeders to select for desirable traits based on DNA patterns rather than just observable characteristics. Modern breeding programs now take this further with genomic selection, which integrates thousands of markers into predictive models, facilitating more efficient and precise breeding decisions.

Climate change is characterized by increasingly extreme weather events, deteriorating soil quality and shifting pest dynamics, posing significant challenges to global agriculture. In response, CRISPR-Cas9 technology has emerged as a transformative genome-editing tool for developing climate-resilient crops. This technique enables precise and targeted modifications of genes associated with stress tolerance, facilitating the rapid generation of crop varieties better adapted to changing environmental conditions. Compared to conventional breeding approaches, CRISPR-Cas9 offers a considerably accelerated timeline for crop improvement, thereby enhancing the capacity to address the urgent demands of food security under climate change (22). Unlike genetic modification, CRISPR offers a non-GMO solution that is gaining acceptance due to its precision in altering existing genes without introducing foreign DNA, making it a more favourable option in many regulatory environments (23).

Editing the *ARGOS8* gene in maize decreases ethylene sensitivity, enabling the plant to grow better under water-limited conditions (24). Similarly, editing the *SUB1A*-like genes in rice mimics the submergence tolerance achieved through traditional breeding (25). Additionally, research indicates that CRISPR/Cas9 to target the *OsRR22* gene in rice, resulting in improved salinity tolerance (26). Further, CRISPR/Cas9 has been used to modify genes like *OsbHLH024* in rice, improving salt tolerance by reducing ROS accumulation and maintaining ion balance (27). Similarly, tweaking nitrate transporter genes like *ZmNRT1.1B* in maize enhances nitrogen-use efficiency, cutting down the need for fertilizers (28). These genetic edits offer a smarter way to boost crop resilience and sustainability. Table 2 shows the genomic technologies employed for utilizing wild relatives.

By combining the strengths of CWRs, molecular breeding tools like DNA markers and genomic selection and innovative gene-editing techniques like CRISPR, plant breeders are well-equipped to develop crops that are more resilient to the stresses brought on by climate change. These advanced strategies represent a multifaceted approach to safeguarding global food security in the face of an uncertain future.

Table 1. Key wild crop relatives and their climate-resilient traits

Wild relative	Cultivated crop	Climate-resilient trait	Reference
Triticum urartu	Wheat	Heat/drought tolerance	(15)
Oryza rufipogon	Rice	Flooding tolerance (submergence)	(16)
Solanum pimpinellifolium	Tomato	Drought resistance	(17)

Table 2. Genomic tools for harnessing wild relatives

Technology	Application	Example study	Reference
CRISPR-Cas9	Editing stress-responsive genes	Tomato wild relative gene editing for drought tolerance	(29)
GWAS (Genome-wide association studies)	Identifying drought-resistance loci	Maize wild relative allele discovery	(30)
Genomic selection	Accelerating introgression pipelines	Genomic selection	(31)

Success Stories: Wild Relatives Driving Crop Adaptation to Climate Change

The world of crop breeding has come a long way in using wild relatives to develop more resilient crops. By tapping into the genetic diversity of wild plants, scientists are creating crops that can withstand the pressures of climate change, like drought, high temperatures and unpredictable weather. Below are several inspiring examples demonstrating the real-world success of this approach.

Wheat– resilience in arid Morocco

In Morocco, the durum wheat variety *Nachit*, released in 2018, exemplifies the successful introgression of traits from wild relatives. Developed by crossing elite wheat lines with wild emmer wheat (*Triticum turgidum* ssp. *dicoccoides*) from Syria, *Nachit* exhibits enhanced drought tolerance and adaptability to arid environments. In addition to its resilience, the variety demonstrates high yield potential, large grain size and elevated protein content, making it a promising cultivar for regions facing increasingly erratic climatic conditions (32).

Wild relatives of durum wheat – enhancing stress tolerance

The incorporation of traits from wild relatives, such as *Triticum turgidum* var. *durum,* has significantly contributed to improved stress tolerance in durum wheat breeding. These wild genotypes provide essential genetic variation for coping with abiotic stresses like drought and salinity. Their integration into breeding programs supports the development of wheat cultivars capable of maintaining productivity under adverse environmental conditions (33).

Sorghum – A model of climate resilience

Sorghum bicolor L. serves as another exemplar of climate adaptation, especially in semi-arid regions of Africa and Asia. Renowned for its ability to grow under low rainfall and high temperatures, sorghum is also well-suited to low-input and marginal agricultural systems. Its domestication, dating back over 5000 years, involved selection for traits such as larger seed size and improved retention, which have culminated in its current form as a highly resilient cereal crop (34).

Pearl millet – adaptation to harsh environments

Pearl millet is among the most drought-tolerant cereals cultivated today, especially prominent in Sub-Saharan Africa. It can thrive in extremely hot and dry conditions, as well as saline soils, with particular robustness during the reproductive phase-a critical period for yield stability. Its domestication has involved both natural and artificial selection, leading to a crop uniquely suited to withstand climate extremes (35).

Amaranth– a sustainable crop for the future

Amaranth (*Amaranthus spp.*) is increasingly recognized for its potential in sustainable agriculture. With origins in Central and South America, it possesses considerable genetic diversity that enables adaptation to poor soils, drought and high temperatures. Additionally, its resistance to pests and diseases makes it a low-maintenance crop. Continuous selection for agronomic traits such as seed size and palatability has strengthened its value as a climate-resilient food source (36).

Challenges in Harnessing Wild Relatives for Modern Breeding Programs

Wild crop relatives (WCRs) offer invaluable genetic diversity for traits like drought tolerance, pest resistance and climate adaptability. Integrating them into modern breeding programs faces significant hurdles:

Genetic incompatibility and reproductive barriers

Many wild crop relatives (WCRs) are distantly related to domesticated crops, resulting in hybrid sterility or inviability due to differences in ploidy levels or chromosomal structures. For instance, crossing wild *Solanum* species with cultivated tomatoes often requires embryo rescue techniques (37). Linkage drag and unwanted Traits of desirable genes in wild crop relatives (WCRs) are often linked to harmful traits, such as low yield, poor taste, or toxicity. Removing these undesirable traits requires time-consuming backcrossing (37). For example, wild rice (*Oryza rufipogon*) offers flood tolerance but also carries undesirable seed-shattering traits. Over 70 % of wild crop relatives (WCRs) are threatened by climate change, urbanization and agriculture, reducing available genetic material (38). Additionally, many WCRs are underrepresented in seed banks due to collection and storage challenges. Introducing wild alleles through transgenic techniques often faces regulatory challenges and public pushback, slowing their acceptance. People are concerned about health risks, environmental impacts and ethical issues, along with fears about corporate control and biodiversity loss. Much of the resistance to genetically modified organisms (GMOs) stems from emotional responses and widespread mistrust of institutions. In Europe, such opposition is further amplified by concerns surrounding globalization and food safety (39, 40). To foster broader acceptance, it is essential to ensure transparent communication, facilitate open public dialogue and establish robust and trustworthy regulatory frameworks.

The Future of Wild Relative Integration in Climate-Smart Crop Breeding

The future of wild relative integration in climate-smart crop breeding looks promising, as advancements in genomics and breeding technologies enable scientists to efficiently identify and incorporate valuable traits from wild plant species CWR into cultivated crops. This significantly enhances their resilience to climate change through traits such as drought tolerance, heat resistance and disease resistance, thus contributing to food security in a changing climate. CWRs have naturally adapted to a variety of environments, making them a valuable source of genetic diversity for strengthening crop resilience. For example, wild wheat species (*Triticum* spp.) have been used to boost resistance to rust diseases, while wild tomato species (*Solanum* spp.) have helped to improve drought tolerance (41, 42). The next decade holds immense promise for genomic-assisted breeding (GAB), thanks to breakthroughs in AI-driven predictive models, CRISPR-based precision editing and high-throughput phenotyping (36, 43, 44, 45). The integration of wild crop relatives, which are rich in stress-resilient traits like drought tolerance and pest resistance, will move from being a niche area of research to mainstream practice. Initiatives like the CWRs have already demonstrated success in enhancing climate resilience by introducing wild alleles into major crops such as wheat and rice (46, 47). Innovations such as pangenome mapping and speed breeding are helping to speed up the process (48, 49). By 2030, these advancements could cut breeding cycles from decades to just a few years, allowing for the rapid development of climate-smart crops that are more productive, sustainable and biodiverse (50). The role of wild crop relatives as reservoirs of climate-resilient traits has been increasingly documented. Fig. 1 presents an overview of these contributions, showcasing introgressed traits and target crops that have benefitted from wild alleles (50-52).

Conclusion

Climate change is reshaping agriculture, requiring innovative solutions to ensure food security in an unpredictable world. At the core of these solutions lies genetic diversity, which is essential for breeding resilient and sustainable crops. Wild relatives, landraces and other genetic resources offer a wealth of traits from drought tolerance to disease resistance that can help crops thrive under stress. Examples like *Swarna-Sub1* rice, which survives prolonged flooding and HD 2967 wheat, designed to endure heat, show the availability of these genetic treasures being translated into real-world solutions. The rise of advanced technologies, such as CRISPR-Cas9 and genomic selection, is revolutionizing breeding, enabling faster and more precise incorporation of resilience traits. When combined with data-driven approaches like machine learning, these tools are shortening the time needed to develop climate-ready crops. This progress gives us hope, but it also brings challenges. The genetic base of many crops is narrowing and valuable wild and exotic germplasm is often neglected or at risk of being lost forever. The path forward requires a collective effort. Farmers, researchers and policymakers must unite to conserve genetic resources, innovate breeding techniques and ensure climate-resilient crops reach the fields where they are most needed. By prioritizing genetic diversity in crop breeding, we enhance current resilience to climate stressors while also equipping future agricultural systems to withstand emerging environmental and biotic threats. Genetic diversity isn't just a technical resource, it's a natural gift and a lifeline. By nurturing and leveraging it wisely, we can create agricultural systems that are more resilient, equitable and sustainable for generations to come.

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Authors' contributions

SRMN wrote the manuscript. SS helped conduct the experiments and contributed to manuscript correction and revision. KP assisted in experiments and participated in manuscript correction and revision. SA was involved in conducting experiments and revising the manuscript. NR contributed to manuscript correction and critical revision. All authors read and approved the final version of the manuscript.

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While preparing this work, the authors used Grammarly to improve the language and readability. After using this tool/ service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

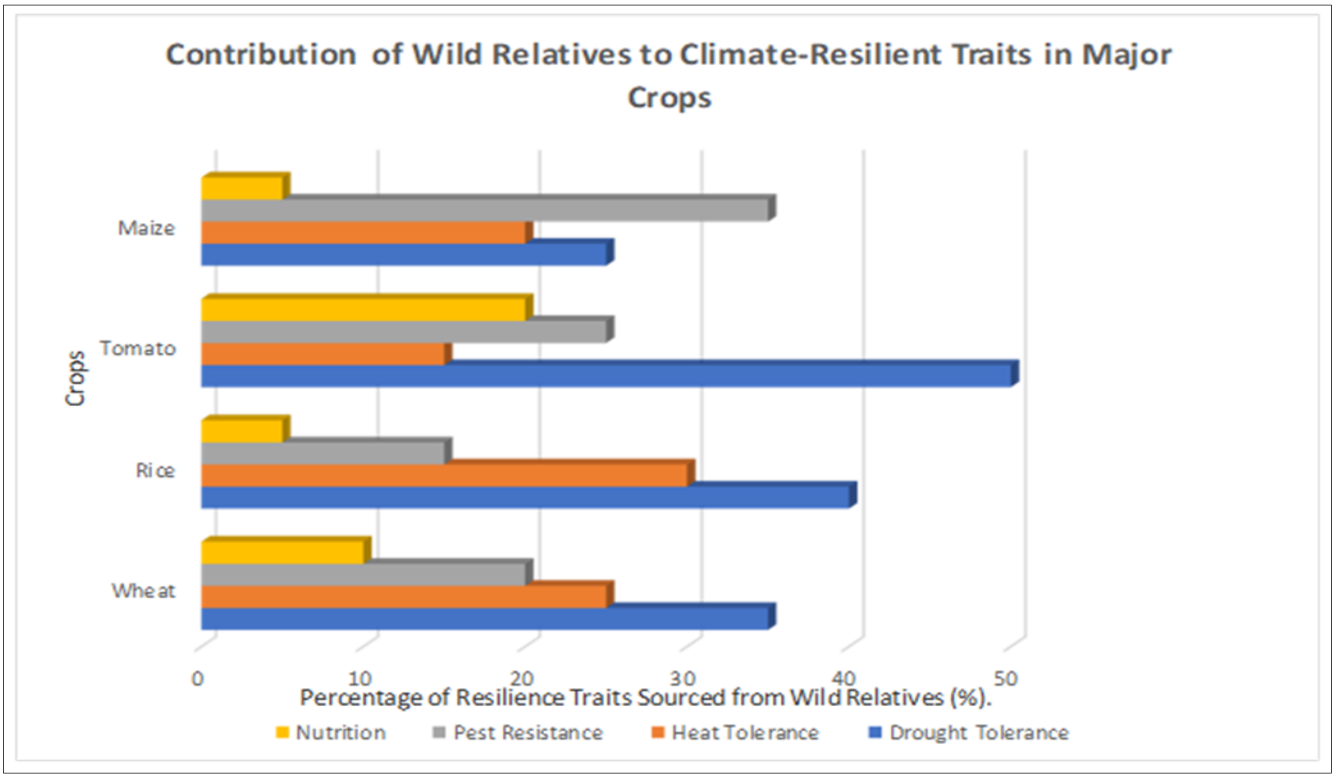

Fig. 1. Contribution of wild relatives to climate-resilient traits in major crops (50-52).

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