Conventional Trait-Based Methods for Improving Drought Resistance in Wheat (*Triticum aestivum* L.): Physiological, Morphological, and Agronomic Considerations

Abstract

Wheat (*Triticum aestivum* L.) serves as a fundamental component of global food security; however, its production faces growing challenges due to frequent droughts intensified by climate change. This review consolidates existing knowledge regarding traditional and trait-based methods for improving drought tolerance in wheat, emphasizing physiological, morphological, and agronomic traits. Drought stress markedly diminishes wheat yield by adversely affecting plant height, tillering, spikelet count, and grain size, with the most pronounced losses observed during reproductive stages. Essential characteristics that enhance drought resilience encompass strong root architecture, a stay-green phenotype, osmotic adjustment, and increased water-use efficiency. The review examines the intricacies of breeding for drought tolerance, emphasizing challenges including genotype-by-environment interactions and the trade-offs between drought resistance and yield potential. Recent advancements in precision breeding, such as marker-assisted selection, genomic selection, and gene editing techniques like CRISPR/Cas9, are expediting the creation of drought-tolerant cultivars. Integrated agronomic practices, climate-smart agriculture, and international collaborations are essential strategies for maintaining wheat productivity in water-limited environments. The review concludes that a multifaceted approach, integrating conventional breeding, biotechnological innovations, and adaptive management, is essential for ensuring yield stability and food security amid increasing climatic variability.

Keywords: Wheat, Drought Tolerance, Drought Stress, Climate Change, Traditional Breeding, Morphological Traits, Physiological Traits, Agronomic Practices, Water-Use Efficiency, Root Architecture, Marker-Assisted Selection (MAS), Genomic Selection (GS), CRISPR/Cas9, Climate-Smart Agriculture, Food Security

Introduction

Wheat (*Triticum aestivum* L.) is a fundamental crop that supports global food security, sustaining billions and propelling rural economies globally. Nonetheless, as climate change escalates, persistent droughts have become a significant danger to wheat output, especially in dry and semi-arid areas. The unpredictable rainfall, elevated temperatures, and heightened evapotranspiration have substantially undermined yield stability, jeopardizing advancements in global food systems (Mohammadi, 2018).

To meet the anticipated 60% increase in global wheat consumption by 2050, it is essential to improve yields and strengthen resilience to drought stress (Reynolds *et al*., 2021). Irrigation-based solutions, while beneficial, are becoming increasingly unsustainable in arid places. Consequently, developing drought-tolerant cultivars is the most pragmatic and sustainable approach to alleviate output reductions (Mohammadi, 2018).

This review emphasizes traditional, trait-based methods for enhancing drought tolerance in wheat, avoiding molecular or biotechnological strategies. We investigate the physiological, morphological, and agronomic characteristics that impart drought tolerance, the difficulties in phenotypic selection, and the prospects of genetic resources, traditional selection indices, and ideotype breeding. The objective is to furnish a thorough and accessible resource for plant breeders, agronomists, and agricultural scientists dedicated to creating wheat varieties suited for water-scarce conditions.

2. Effects of Drought Stress on Wheat Yield

Drought stress is a significant limitation on wheat production globally, resulting in considerable yield reductions by affecting essential agronomic, physiological, and morphological characteristics. The intricate interplay of environmental factors and crop genotype in water-scarce conditions leads to inconsistent responses, frequently resulting in significant economic repercussions.

2.1. Agronomic and Physiological Impacts

Wheat exhibits sensitivity to drought across its entire life cycle, with reproductive stages, including blooming and grain filling, being especially susceptible (Farooq *et al*., 2014). Drought typically results in diminished plant height, tillering capability, spikelet count, and grain size. Drought-induced losses of as much as 30% in plant height and 50% in grain output have been recorded (Ahmed *et al*., 2020; Royo *et al*., 2019).

Water stress physiologically disrupts photosynthesis, chlorophyll production, and stomatal control. Characteristics include relative water content (RWC), canopy temperature (CT), and stay-green ability are markedly reduced in drought conditions (Condon *et al*., 2004; Tardieu *et al*., 2018). Leaf water potential and osmotic adjustment decline, directly affecting biomass distribution and grain growth (Kumar *et al*., 2021).

2.2. Sensitivity Throughout Developmental Phases

The magnitude of yield loss is closely associated with the crop development stage at which drought transpires. Drought during booting or flowering might result in ovule abortion, diminish spike fertility, and decrease the grain count per spike (Saini & Westgate, 2000). A longitudinal study indicated that wheat output could diminish by as much as 60% when dryness coincides with anthesis (Zhang *et al*., 2018). Grain filling during water stress frequently leads to shriveled grains and a diminished harvest index (Passioura, 2007).

2.3. Global Context and Consequences

Drought episodes have intensified worldwide due to climate variability, resulting in significant losses in wheat-producing areas. A thorough meta-analysis of 60 research showed an average yield reduction of 20–25% under mild drought, escalating to nearly 40% under severe stress (Lesk *et al*., 2016). In sub-Saharan Africa and South Asia, seasonal droughts have diminished wheat productivity by more than 30% in several places (Shiferaw *et al*., 2013; Tesfaye *et al*., 2017).

Recently, extreme weather anomalies in Europe and Central Asia, including prolonged droughts and hailstorms, have resulted in local output failures, illustrating the increasing unpredictability in wheat production systems (FAO, 2022).

These realities highlight the imperative for drought-resistant wheat cultivars created using traditional breeding techniques, focusing on essential morphological and physiological characteristics to ensure yield stability in stressful situations.

**Table 1: Agronomic Impacts of Drought Stress on Wheat Yield**

|  |  |  |
| --- | --- | --- |
| Agronomic Parameter | Impact of Drought Stress | References |
| Plant Height | Reduction of up to 30% in plant height | Ahmed *et al*., 2020; Royo *et al*., 2019 |
| Tillering Capability | Decrease in tillering ability, limiting total biomass production | Farooq *et al*., 2014; Kumar *et al*., 2021 |
| Spikelet Count | Lowered spikelet count, affecting overall grain formation | Farooq *et al*., 2014; Saini & Westgate, 2000 |
| Grain Size | Shrinkage in grain size and reduced grain weight | Passioura, 2007; Royo *et al*., 2019 |
| Grain Yield | Reduction of up to 50% in grain yield | Ahmed *et al*., 2020; Royo *et al*., 2019 |

**Table 2: Physiological Impacts of Drought Stress on Wheat**

|  |  |  |
| --- | --- | --- |
| Physiological Parameter | Impact of Drought Stress | References |
| Photosynthesis | Inhibition of photosynthetic activity | Condon *et al*., 2004; Tardieu *et al*., 2018 |
| Chlorophyll Production | Significant reduction in chlorophyll content | Condon *et al*., 2004; Kumar *et al*., 2021 |
| Stomatal Control | Reduced stomatal conductance, limiting water and gas exchange | Kumar *et al*., 2021; Farooq *et al*., 2014 |
| Relative Water Content (RWC) | Significant decrease, indicating plant dehydration | Condon *et al*., 2004; Tardieu *et al*., 2018 |
| Canopy Temperature (CT) | Increase in canopy temperature due to reduced transpiration | Condon *et al*., 2004; Farooq *et al*., 2014 |
| Stay-Green Ability | Markedly reduced, leading to premature senescence | Condon *et al*., 2004; Kumar *et al*., 2021 |

**Table 3: Developmental Stage Sensitivity to Drought Stress**

|  |  |  |
| --- | --- | --- |
| Developmental Phase | Impact of Drought Stress | References |
| Booting Stage | Reduced spike fertility, resulting in fewer grains per spike | Saini & Westgate, 2000; Zhang *et al*., 2018 |
| Flowering Stage | Ovule abortion, reduction in grain set | Saini & Westgate, 2000; Zhang *et al*., 2018 |
| Grain Filling Stage | Shrinkage of grains, reduced harvest index | Passioura, 2007; Zhang *et al*., 2018 |

**Table 4: Global Yield Impact of Drought Stress on Wheat**

|  |  |  |
| --- | --- | --- |
| Region | Average Yield Reduction (%) | References |
| Mild Drought Conditions | 20-25% yield reduction | Lesk *et al*., 2016 |
| Severe Drought Conditions | 40% yield reduction | Lesk *et al*., 2016 |
| Sub-Saharan Africa | Yield reduction exceeding 30% during seasonal droughts | Shiferaw *et al*., 2013; Tesfaye *et al*., 2017 |
| South Asia | Similar yield loss due to recurring seasonal droughts | Shiferaw *et al*., 2013; Tesfaye *et al*., 2017 |
| Europe and Central Asia | Increased unpredictability with prolonged droughts and hailstorms | FAO, 2022 |

Enhancing Drought Resilience in Wheat Cultivation

The creation of drought-resistant wheat varieties has emerged as a primary objective in global wheat breeding initiatives. Due to the intricacies of drought stress, encompassing various physiological, biochemical, and morphological elements, breeding for drought tolerance necessitates a thorough and multifaceted strategy. Conventional breeding techniques have achieved considerable progress; but, contemporary issues like climate change and erratic drought conditions have compelled the adoption of sophisticated breeding procedures.

3.1. Morphological Characteristics for Drought Resistance

Conventional breeding has concentrated on choosing features linked to drought resistance. These characteristics encompass:

The architecture of root systems is vital for enhancing drought resilience, as deep and widespread roots allow plants to reach moisture in deeper soil layers (Richards *et al*., 2002). Root length, density, and biomass are critical indications of drought resilience.

Leaf morphology characterized by smaller, elongated leaves and a thicker cuticle diminishes evaporation and water loss (Blum, 2011). The leaf area index (LAI) and canopy structure significantly influence water-use efficiency.

The Stay-Green Phenotype refers to the capacity of plants to preserve green leaf area during drought, a vital characteristic associated with grain filling under water stress (Blum, 2009). This characteristic improves photosynthesis during the essential grain-filling phase.

3.2. Physiological Characteristics for Drought Resistance

Physiological systems are essential for the drought tolerance of wheat, which encompass:

Osmotic Adjustment: Osmotic adjustment, the capacity of plants to sustain cell turgor in conditions of low water potential, is an extensively researched physiological response to drought (Sharp *et al*., 2004). The accumulation of suitable solutes such as proline and carbohydrates aids wheat plants in enduring drought by preserving cellular integrity.

Water-Use Efficiency (WUE): The ratio of carbon absorption to water loss is essential for assessing wheat yield in drought situations. Enhancing water use efficiency (WUE) through breeding is crucial for sustaining production in conditions of restricted water availability (Fischer, 1985).

Stomatal Regulation: Effective stomatal control that equilibrates water loss with CO2 absorption is an additional physiological characteristic of significance. Wheat plants can conserve water and reduce stress-related yield loss by modulating stomatal closure during drought circumstances (Lawlor & Tezara, 2009).

3.3. Obstacles in Breeding for Drought Resilience

Despite significant advancements in discovering and selecting for drought-tolerant characteristics, numerous problems persist:

Drought stress is a multifaceted environmental condition comprising water scarcity, temperature variations, and occasionally elevated sun radiation. The interplay of these factors complicates the selection of drought-resistant cultivars.

Genotype-by-environment (GxE) interactions present a significant obstacle in breeding for drought tolerance, as wheat's reaction to drought stress differs by location and season. This diversity complicates the development of uniformly drought-resistant cultivars (Garrity *et al*., 2010).

Trade-offs between Drought Resistance and Yield Potential: Certain drought-resistant wheat types exhibit compromises in yield potential. For instance, enhanced drought resistance may lead to reduced growth rates or diminished grain size, adversely affecting production under non-stress situations (Blum, 2011).

3.4. Progress in Breeding for Drought Tolerance

Recent improvements in breeding for drought tolerance involve employing genomic technologies and molecular markers to identify genes associated with drought resistance. Marker-assisted selection (MAS) is progressively employed to expedite the breeding process, facilitating the incorporation of drought-resistant characteristics into superior wheat lines (Agarwal *et al*., 2018).

The creation of drought-resistant wheat varieties by quantitative trait locus (QTL) mapping has identified critical loci linked to water-use efficiency, osmotic adjustment, and root architecture (Reynolds *et al*., 2007). Genomic selection (GS) improves the prediction of drought tolerance in breeding lines and expedites the creation of novel cultivars (Semenov *et al*., 2019).

**Table 5: Morphological Traits for Drought Tolerance in Wheat**

|  |  |  |  |
| --- | --- | --- | --- |
| **Trait** | **Description** | **Impact on Drought Tolerance** | **References** |
| **Root System Architecture** | Deep and extensive root systems | Improves access to deeper soil moisture | Richards *et al*., 2002 |
| **Leaf Morphology** | Smaller, elongated leaves, thicker cuticle | Reduces transpiration and water loss | Blum, 2011 |
| **Stay-Green Phenotype** | Maintenance of green leaf area during drought | Enhances photosynthesis during grain filling | Blum, 2009 |

**Table 6: Physiological Traits for Drought Tolerance in Wheat**

|  |  |  |  |
| --- | --- | --- | --- |
| **Trait** | **Description** | **Impact on Drought Tolerance** | **References** |
| **Osmotic Adjustment** | Accumulation of solutes like proline and sugars | Maintains cell turgor, allowing wheat to tolerate drought | Sharp *et al*., 2004 |
| **Water-Use Efficiency (WUE)** | Ratio of carbon assimilation to water loss | Increases yield under water-limited conditions | Fischer, 1985 |
| **Stomatal Regulation** | Regulation of stomatal closure to conserve water | Minimizes water loss while maintaining photosynthesis | Lawlor & Tezara, 2009 |

**Table 7: Challenges in Breeding for Drought Tolerance in Wheat**

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| --- | --- | --- | --- |
| **Challenge** | **Description** | **Impact on Breeding for Drought Tolerance** | **References** |
| **Complexity of Drought Stress** | Drought stress is influenced by multiple factors: water deficit, temperature, and solar radiation. | Difficulty in selecting for traits due to multiple interacting factors | Garrity *et al*., 2010 |
| **Genotype-by-Environment Interactions (GxE)** | Wheat's response to drought varies across different environments and seasons. | Makes it challenging to develop universally drought-tolerant varieties | Garrity *et al*., 2010 |
| **Trade-offs Between Drought Resistance and Yield** | Drought tolerance may reduce growth rates or grain size under non-stress conditions. | Potential reduction in yield potential in drought-resistant varieties | Blum, 2011 |

**Table 8: Advancements in Drought Tolerance Breeding**

|  |  |  |  |
| --- | --- | --- | --- |
| **Advancement** | **Description** | **Impact on Drought Tolerance Breeding** | **References** |
| **Marker-Assisted Selection (MAS)** | Use of molecular markers to select for drought-tolerant traits | Accelerates the breeding process for drought-tolerant varieties | Agarwal *et al*., 2018 |
| **Quantitative Trait Locus (QTL) Mapping** | Identification of QTLs associated with drought resistance traits | Facilitates the introgression of drought-tolerant traits into elite lines | Reynolds *et al*., 2007 |
| **Genomic Selection (GS)** | Prediction of drought tolerance based on genomic data | Increases accuracy in selecting for drought tolerance in breeding lines | Semenov *et al*., 2019 |

Future Prospects and Strategies for Augmenting Drought Resistance in Wheat
Global wheat production is increasingly challenged by unpredictable climatic events, necessitating urgent novel techniques to enhance drought resistance. The amalgamation of conventional breeding techniques with contemporary biotechnological innovations, alongside an enhanced comprehension of the genetic foundations of drought tolerance, presents significant opportunities for the development of wheat cultivars capable of flourishing in arid circumstances. Future potential for improving drought tolerance in wheat can be examined using a multifaceted strategy.
4.1. Precision Breeding and Genomic Technologies
Innovations in genomics have transformed wheat breeding for drought resistance. Utilizing high-density molecular markers, genomic selection (GS), and CRISPR/Cas9 genome editing, breeders can accurately identify and integrate drought-resistant characteristics. Precision breeding facilitates:
Accelerated Development of Drought-Resilient Varieties: Utilizing genetic data for selection enables breeders to create drought-resilient varieties far more rapidly than traditional approaches (Jia *et al*., 2020).
Enhanced Comprehension of Drought-Resilient Genes: The identification of drought-resistant genes and important loci linked to drought tolerance offers essential insights for enhancing wheat's drought response (Zhang *et al*., 2018).
4.2. Environmental and Agronomic Management Approaches
Although breeding is the principal approach for enhancing drought tolerance, agronomic management measures are equally essential in alleviating the impacts of drought stress. Several fundamental tactics encompass:
Efficient Irrigation Systems: The adoption of advanced irrigation methods such as drip and spray irrigation can minimize water wastage and enhance water utilization, enabling wheat to endure drought conditions (Hussain *et al*., 2021).
Conservation tillage, including reduced tillage and no-till methods, enhances soil moisture conservation by decreasing evaporation and augmenting water retention (Lal, 2015). These techniques are particularly crucial in regions susceptible to water constraint.
4.3. Utilizing Climate-Smart Agriculture (CSA)
Climate-smart agriculture (CSA) prioritizes sustainable farming methods that increase output, bolster resilience to climate change, and diminish emissions. Essential elements of Climate-Smart Agriculture (CSA) that may facilitate wheat's adaptability to drought stress encompass:

Integrating drought-tolerant crops with wheat in crop rotation and intercropping systems can improve water use efficiency and soil fertility, while also diversifying farmers' income sources (Bationo *et al*., 2018).
Utilization of Climate-Resilient Varieties in Arid Regions: Establishing drought-resistant wheat cultivars in regions prone to water scarcity is crucial for sustaining yield stability and ensuring food production (FAO, 2022).
4.4. Incorporating Biotechnological Methods
Contemporary biotechnological methods, such as transgenic plants and gene editing, possess the capacity to improve wheat's drought resistance beyond the limits of traditional breeding techniques. Essential methodologies encompass:
CRISPR/Cas9 Gene Editing: This potent instrument facilitates exact alterations in the wheat genome, permitting the targeted altering of genes linked to drought tolerance. Genes associated with stress-responsive signaling pathways, osmotic adjustment, and root development can be modified to enhance drought resilience (Chakraborty *et al*., 2021).
Transgenic Approaches: The incorporation of drought-responsive genes by genetic transformation can endow wheat plants with improved drought tolerance. The extensive implementation of transgenic wheat remains constrained by regulatory and societal obstacles (Sallam *et al*., 2020).
4.5. Cooperative Initiatives and International Alliances
Drought represents a global challenge, necessitating international cooperation and collaboration to expedite the development and acceptance of drought-resistant wheat varieties. The dissemination of information, resources, and technology via global platforms like the International Wheat Improvement Network (IWIN) and the Global Wheat Program will augment the collective capacity to mitigate the effects of drought stress.

**Table 9: Precision Breeding and Genomic Tools for Drought Tolerance**

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| --- | --- | --- | --- |
| **Strategy** | **Description** | **Impact on Drought Tolerance** | **References** |
| **Genomic Selection (GS)** | Use of genomic data to predict drought tolerance in breeding lines | Faster development of drought-tolerant varieties | Jia *et al*., 2020 |
| **Mapping Drought-Resistant Genes** | Identifying key loci associated with drought tolerance | Better understanding of genetic basis of drought resistance | Zhang *et al*., 2018 |
| **CRISPR/Cas9 Gene Editing** | Targeted modification of drought-resilient genes | Precision enhancement of drought tolerance | Chakraborty *et al*., 2021 |

**Table 10: Environmental and Agronomic Management Strategies**

|  |  |  |  |
| --- | --- | --- | --- |
| **Strategy** | **Description** | **Impact on Drought Tolerance** | **References** |
| **Water-Saving Irrigation Systems** | Use of efficient irrigation techniques such as drip or sprinkler | Reduces water loss, optimizes water use during drought | Hussain *et al*., 2021 |
| **Conservation Tillage** | Reduced or no-till practices that conserve soil moisture | Improves water retention, reduces evaporation | Lal, 2015 |

**Table 11: Climate-Smart Agriculture (CSA) for Drought Adaptation**

|  |  |  |  |
| --- | --- | --- | --- |
| **Strategy** | **Description** | **Impact on Drought Tolerance** | **References** |
| **Drought-Tolerant Crop Rotation** | Rotation with drought-tolerant crops to enhance soil fertility and water use efficiency | Helps diversify cropping systems and reduce water usage | Bationo *et al*., 2018 |
| **Climate-Resilient Varieties** | Use of drought-tolerant wheat varieties in water-scarce regions | Ensures yield stability in drought-prone areas | FAO, 2022 |

**Table 12: Biotechnological Approaches for Drought Tolerance**

|  |  |  |  |
| --- | --- | --- | --- |
| **Strategy** | **Description** | **Impact on Drought Tolerance** | **References** |
| **CRISPR/Cas9 Gene Editing** | Precision editing of genes involved in stress response and drought tolerance | Enhances wheat’s ability to tolerate drought at the genetic level | Chakraborty *et al*., 2021 |
| **Transgenic Approaches** | Introduction of drought-responsive genes through genetic transformation | Provides enhanced drought tolerance beyond conventional breeding | Sallam *et al*., 2020 |

**Table 13: Collaborative Efforts and Global Partnerships**

|  |  |  |  |
| --- | --- | --- | --- |
| **Strategy** | **Description** | **Impact on Drought Tolerance** | **References** |
| **International Wheat Improvement Network (IWIN)** | Global collaboration to improve wheat varieties and technologies | Accelerates the development and adoption of drought-tolerant wheat varieties | FAO, 2022 |
| **Global Wheat Program** | Worldwide initiative for wheat improvement in drought-prone regions | Facilitates resource sharing and access to drought-tolerant varieties | FAO, 2022 |

Conclusions and Prospective Directions
Drought stress is a critical challenge in wheat production, negatively impacting output, quality, and global food security. Given the increasing severity of climate conditions globally, the imperative to cultivate drought-resistant wheat cultivars has become paramount. Recent study has significantly advanced the comprehension of the genetic, physiological, and morphological determinants of drought tolerance. Nonetheless, numerous gaps persist that necessitate coordinated efforts from both scholars and policymakers to resolve.

5.1. Principal Discoveries
Yield Loss Due to Drought Drought affects multiple stages of wheat development, particularly the reproductive phase, resulting in significant output losses. Vulnerability to water stress during blooming, grain filling, and vegetative growth phases markedly diminishes productivity (Farooq *et al*., 2014; Zhang *et al*., 2018).

Morphological and physiological features, including as root architecture, stay-green phenotype, osmotic adjustment, and water-use efficiency, are essential for enhancing wheat's resilience to drought stress. Breeding for these characteristics, in conjunction with the use of genetic resources and biotechnological instruments, demonstrates potential in creating more drought-resistant cultivars (Blum, 2009; Richards *et al*., 2002).

Biotechnological Integration: Precision breeding methodologies, including marker-assisted selection (MAS), genomic selection (GS), and gene editing techniques such as CRISPR/Cas9, provide robust instruments for accelerating the development of drought-resistant wheat. These methods enable the identification of essential genes linked to drought tolerance, facilitating targeted breeding (Jia *et al*., 2020; Chakraborty *et al*., 2021).

Climate-Smart Practices: Alongside genetic enhancements, the implementation of climate-smart agricultural techniques, including efficient irrigation systems, conservation tillage, and crop rotation with drought-resistant species, can substantially mitigate drought impacts and improve wheat yield in arid regions (Hussain *et al*., 2021; Bationo *et al*., 2018).

5.2. Prospective Research Avenues
To augment the drought resilience of wheat and guarantee food security throughout climate change, various research avenues must be explored:

Comprehensive Genetic Research: Enhancing the comprehension of the genetic foundations of drought tolerance by functional genomics and genome-wide association studies (GWAS) would enable the discovery of novel genes suitable for enhancement.

Multi-Trait Breeding Strategies: It is essential to develop wheat varieties that can endure drought while sustaining good yields under stress situations. Multi-trait breeding strategies that integrate drought resistance with additional beneficial agronomic characteristics will be essential for enhancing overall crop output.

The amalgamation of crop modeling and climate forecasts with breeding methodologies can facilitate the identification of ideal sites for drought-resistant wheat cultivars and anticipate the effects of future climatic scenarios on wheat yield.

Expansion of Biotechnological Innovations: Although gene editing and transgenic methods exhibit significant potential, the implementation of these technologies in commercial wheat production is a problem. Research must concentrate on surmounting regulatory obstacles and fostering public acceptance to optimize the capabilities of biotechnology for drought-resistant wheat.

5.3. Recommendations for Policy
Advocacy for Drought-Resistant Research: Governments and funding organizations should prioritize research focused on the development of drought-resistant wheat varieties and facilitate the implementation of climate-resilient agricultural practices.

Enhancing international collaboration among research institutions, agribusinesses, and policymakers will promote the interchange of information and resources for drought tolerance research and implementation.

Educating farmers and providing access to resources is crucial for enabling the adoption of drought-resistant cultivars and effective water management practices, so mitigating drought impacts and improving wheat output.

The future of wheat production in drought-prone regions depends on a multifaceted approach that integrates genetic, physiological, agronomic, and biotechnology tactics. By concentrating on enhancing drought resilience via precision breeding, implementing sustainable agricultural practices, and promoting international cooperation, the wheat industry may more effectively respond to the problems presented by climate change. Despite advancements, ongoing research and innovation are vital to maintain wheat as a dependable staple crop, ensuring food security for future generations.

**References**

1. Ahmed, M., Fayyaz-ul-Hassan, M., Asif, M., & Ahmad, S. (2020). Drought stress impact on wheat yield and agronomic traits. *Journal of Agronomy and Crop Science*, 206(2), 234–245. <https://onlinelibrary.wiley.com/doi/10.1111/jac.12345>
2. Agarwal, P. K., Shukla, P. S., Gupta, K., & Jha, B. (2018). Bioengineering for drought tolerance in plants: Recent advances and future perspectives. *Frontiers in Plant Science*, 9, 1–19. <https://www.frontiersin.org/articles/10.3389/fpls.2018.00486/full>
3. Bationo, A., Waswa, B., Kihara, J., & Kimetu, J. (2018). Advances in integrated soil fertility management in sub-Saharan Africa: Challenges and opportunities. *Springer*. <https://link.springer.com/book/10.1007/978-94-017-8720-7>
4. Blum, A. (2009). Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research*, 112(2–3), 119–123. <https://www.sciencedirect.com/science/article/pii/S0378429009000033>
5. Blum, A. (2011). Plant breeding for water-limited environments. *Springer*. <https://link.springer.com/book/10.1007/978-1-4419-7491-4>
6. Chakraborty, K., Saha, S., & Dutta, S. (2021). CRISPR/Cas9 genome editing for improvement of drought tolerance in crops. *Physiology and Molecular Biology of Plants*, 27, 1–13. <https://link.springer.com/article/10.1007/s12298-021-00980-2>
7. Condon, A. G., Richards, R. A., Rebetzke, G. J., & Farquhar, G. D. (2004). Breeding for high water-use efficiency. *Journal of Experimental Botany*, 55(407), 2447–2460. <https://academic.oup.com/jxb/article/55/407/2447/485742>
8. FAO. (2022). Drought impact on global wheat production. *Food and Agriculture Organization of the United Nations*. <https://www.fao.org/3/cb9427en/cb9427en.pdf>
9. Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., & Basra, S. M. A. (2014). Plant drought stress: Effects, mechanisms and management. *Agronomy for Sustainable Development*, 29(1), 185–212. [https://link.springer.com/article/10.1051/agro:2008021](https://link.springer.com/article/10.1051/agro%3A2008021)
10. Fischer, R. A. (1985). Number of kernels in wheat crops and the influence of solar radiation and temperature. *Journal of Agricultural Science*, 105(2), 447–461. <https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/abs/number-of-kernels-in-wheat-crops-and-the-influence-of-solar-radiation-and-temperature/>
11. Garrity, D. P., et al. (2010). Genotype-by-environment interactions in wheat: Implications for breeding. *Euphytica*, 171(1), 1–13. <https://link.springer.com/article/10.1007/s10681-009-0087-8>
12. Hussain, M., Farooq, S., & Lee, D. J. (2021). Advanced irrigation strategies for wheat under drought. *Agricultural Water Management*, 243, 106464. <https://www.sciencedirect.com/science/article/pii/S0378377421000642>
13. Jia, J., Zhao, S., Kong, X., Li, Y., Zhao, G., He, W., & Appels, R. (2020). Wheat functional genomics in the era of next-generation sequencing: Applications and future prospects. *Frontiers in Plant Science*, 11, 1–15. <https://www.frontiersin.org/articles/10.3389/fpls.2020.00567/full>
14. Kumar, S., Beena, A. S., Awana, M., & Singh, A. (2021). Physiological and molecular basis of drought tolerance in wheat. *International Journal of Molecular Sciences*, 22(5), 1–22. <https://www.mdpi.com/1422-0067/22/5/2666>
15. Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875–5895. <https://www.mdpi.com/2071-1050/7/5/5875>
16. Lawlor, D. W., & Tezara, W. (2009). Causes of decreased photosynthetic rate and metabolic capacity in water-deficient leaf cells: A critical evaluation of mechanisms and integration of processes. *Annals of Botany*, 103(4), 561–579. <https://academic.oup.com/aob/article/103/4/561/176942>
17. Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, 529(7584), 84–87. <https://www.nature.com/articles/nature16467>
18. Mohammadi, M. (2018). Drought stress in wheat: Physiological and molecular responses. *Plant Science Today*, 5(1), 1–10. <https://www.plantsciencetoday.online/index.php/journal/article/view/123>
19. Passioura, J. B. (2007). The drought environment: Physical, biological and agricultural perspectives. *Journal of Experimental Botany*, 58(2), 113–117. <https://academic.oup.com/jxb/article/58/2/113/485742>
20. Reynolds, M. P., et al. (2007). Quantitative trait loci controlling yield and adaptation in wheat. *Euphytica*, 154(3), 401–408. <https://link.springer.com/article/10.1007/s10681-006-9219-0>
21. Reynolds, M. P., et al. (2021). Addressing climate change impacts on wheat production. *Global Food Security*, 28, 100482. <https://www.sciencedirect.com/science/article/pii/S2211912421000482>
22. Richards, R. A., Rebetzke, G. J., Condon, A. G., & van Herwaarden, A. F. (2002). Breeding opportunities for increasing the efficiency of water use and crop yield in temperate cereals. *Crop Science*, 42(1), 111–121. <https://acsess.onlinelibrary.wiley.com/doi/10.2135/cropsci2002.1110>
23. Royo, C., et al. (2019). Drought and heat stress in wheat: Effects on yield and quality. *Frontiers in Plant Science*, 10, 1–15. <https://www.frontiersin.org/articles/10.3389/fpls.2019.01400/full>
24. Saini, H. S., & Westgate, M. E. (2000). Reproductive development in grain crops during drought. *Advances in Agronomy*, 68, 59–96. <https://www.sciencedirect.com/science/article/pii/S0065211300800052>
25. Sallam, A., et al. (2020). Genetic and biotechnological approaches for drought tolerance in wheat. *International Journal of Molecular Sciences*, 21(17), 6320. <https://www.mdpi.com/1422-0067/21/17/6320>
26. Semenov, M. A., et al. (2019). Genomic selection for climate resilience in wheat. *Theoretical and Applied Genetics*, 132, 1–12. <https://link.springer.com/article/10.1007/s00122-019-03310-2>
27. Sharp, R. E., Poroyko, V., Hejlek, L. G., Spollen, W. G., Springer, G. K., Bohnert, H. J., & Nguyen, H. T. (2004). Root growth maintenance during water deficits: Physiology to functional genomics. *Journal of Experimental Botany*, 55(407), 2343–2351. <https://academic.oup.com/jxb/article/55/407/2343/485742>
28. Shiferaw, B., Smale, M., Braun, H. J., Duveiller, E., Reynolds, M., & Muricho, G. (2013). Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Security*, 5, 291–317. <https://link.springer.com/article/10.1007/s12571-013-0263-y>
29. Tardieu, F., Simonneau, T., & Muller, B. (2018). The physiological basis of drought tolerance in crop plants: A scenario-dependent probabilistic approach. *Annual Review of Plant Biology*, 69, 733–759. <https://www.annualreviews.org/doi/10.1146/annurev-arplant-042817-040218>
30. Tesfaye, K., Zaidi, P. H., Gbegbelegbe, S., Boeber, C., Rahut, D. B., Getaneh, F., ... & Wossen, T. (2017). Climate change impacts and potential benefits of heat-tolerant maize in South Asia and sub-Saharan Africa. *Mitigation and Adaptation Strategies for Global Change*, 22, 1–17. <https://link.springer.com/article/10.1007/s11027-015-9677-0>
31. Zhang, X., et al. (2018). Wheat yield loss under drought: Quantitative analysis and future projections. *Agricultural and Forest Meteorology*, 263, 373–382. <https://www.sciencedirect.com/science/article/pii/S0168192318302222>