

Breeding the Next Generation of Water-Efficient Crops

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INTRODUCTION

Water is essential for agricultural productivity and global food security, but increasing population growth, climate change, urbanization, and industrial expansion are putting severe pressure on freshwater resources. Agriculture alone consumes nearly 70% of the world's freshwater, while droughts, irregular rainfall, groundwater depletion and rising temperatures are continuously reducing water availability for crop production. Water scarcity has become a major threat to agriculture, particularly in arid and semi-arid regions. Drought stress negatively affects plant growth, photosynthesis, nutrient absorption, flowering, grain filling and final crop yield. Important food crops such as rice, wheat, maize, and soybean are highly sensitive to water shortages during critical growth stages, leading to significant productivity losses.



To address these challenges, scientists are focusing on breeding water-efficient crops that can produce higher yields with less water. These crops are designed to use water more efficiently, tolerate drought conditions, reduce irrigation requirements and improve resilience to climate stress. Water-efficient varieties play a crucial role in sustainable agriculture and future food security.

Need for Water-Efficient Crops

The demand for water-efficient crops is increasing rapidly due to several global challenges.

Challenge	Impact on Agriculture
Climate change	Increased drought frequency and heat stress
Groundwater depletion	Reduced irrigation availability
Population growth	Rising food demand
Urbanization	Competition for water resources
Land degradation	Reduced soil water-holding capacity
Erratic rainfall	Unstable crop production

Water scarcity is already affecting millions of hectares of agricultural land globally. According to recent studies, drought stress can reduce crop yields by 20-70% depending on crop species and severity of stress. Developing

crops with improved water-use efficiency and drought tolerance is therefore essential for ensuring sustainable food production in the future.

Understanding Water-Use Efficiency (WUE)

Water-use efficiency (WUE) refers to the ability of a plant to produce biomass or yield per unit of water used. It is one of the most important traits targeted in drought-resilient crop breeding.

Type	Description
Agronomic WUE	Yield produced per unit of water applied
Physiological WUE	Biomass produced per unit of transpired water
Transpiration Efficiency	Carbon gain relative to water loss
Irrigation WUE	Yield obtained per unit irrigation water

Improving WUE enables crops to maintain productivity under limited water availability. Research indicates that improving transpiration efficiency, biomass accumulation, and carbon partitioning are key strategies for breeding water-efficient crops.



Physiological Traits of Water-Efficient Crops

1. Deep and Efficient Root Systems

Root architecture is a key factor influencing water uptake and drought tolerance in crops. Plants with deeper and more extensive root systems can efficiently access moisture from deeper soil layers, allowing them to survive under limited water conditions. Improved root systems enhance water absorption, nutrient uptake and drought resilience while reducing wilting stress. Deep-rooted crops such as sorghum, pearl millet and drought-tolerant wheat varieties are therefore better adapted to water-scarce environments and can maintain productivity under drought conditions.

2. Reduced Transpiration Loss

Water-efficient crops possess specialized physiological adaptations that help reduce water loss through transpiration. These crops regulate stomatal opening to conserve moisture during drought conditions. Mechanisms such as smaller stomatal apertures, waxy leaf coatings, leaf rolling, and reduced leaf area help limit excessive water evaporation from plant surfaces. Together, these adaptations improve water conservation, enhance drought tolerance

and enable crops to maintain growth and productivity under limited water availability.

3. Osmotic Adjustment

Under water stress conditions, plants accumulate compatible solutes such as proline, glycine betaine, sugars, and amino acids to protect cellular functions. These compounds help maintain cell turgor, stabilize proteins and membranes, and support normal metabolic activities during drought stress. The accumulation of these osmoprotectants enhances the plant's ability to tolerate dehydration and improves survival under limited water availability.

4. Improved Photosynthetic Efficiency

Some drought-tolerant crops can sustain photosynthesis even under limited water availability through several adaptive mechanisms. These include enhanced chlorophyll stability, improved carbon fixation efficiency, and better functioning of photosynthetic enzymes during stress conditions. In addition, specialized photosynthetic pathways such as C4 and CAM help plants conserve water while maintaining energy production.

Conventional Breeding for Water Efficiency

Major Conventional Breeding Methods

Method	Purpose
Selection breeding	Identify naturally drought-tolerant plants
Hybridization	Combine favorable drought-tolerance traits
Backcross breeding	Transfer drought-resistance genes
Mutation breeding	Generate stress-tolerant variants

Molecular Breeding Approaches

1. Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) is an advanced breeding technique that uses molecular markers linked to drought-tolerance genes to develop water-efficient crop varieties. This approach enables faster and more accurate selection of desirable traits, allows early-stage

screening of plants and significantly reduces breeding time compared to conventional methods. Molecular markers such as SSRs (Simple Sequence Repeats) and SNPs (Single Nucleotide Polymorphisms) are widely used in drought-resistance breeding programs to identify and select superior genotypes with improved tolerance to water stress.

2. Quantitative Trait Loci (QTL) Mapping

QTL mapping helps identify genomic regions linked to drought-tolerance traits such as root depth, stomatal conductance, yield under stress and water-use efficiency. This technique supports the development of drought-resilient crops and has improved drought tolerance in rice, maize and wheat.

3. Genomic Selection

Genomic selection uses genome-wide molecular markers and computational models to predict breeding performance and select superior genotypes. This approach accelerates breeding cycles, improves prediction accuracy and efficiently manages complex traits such as drought tolerance and water-use efficiency.

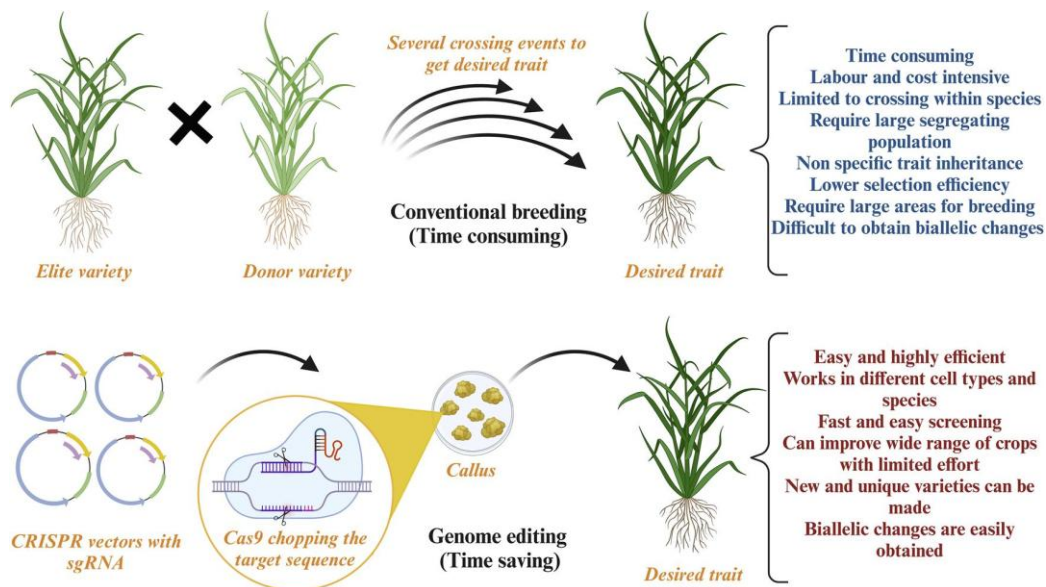
Gene Editing and Biotechnology

Gene editing technologies such as CRISPR-Cas enable precise modification of drought-

tolerance genes involved in root development, stress signalling, water conservation and hormonal regulation. This approach is faster than conventional breeding and helps improve crop yield stability under drought conditions.

Transgenic Approaches

Genetic engineering enables the transfer of drought-tolerance genes from other organisms to improve crop resilience. For example, HB4 Wheat contains a sunflower-derived gene that enhances drought tolerance and yield stability under water-limited conditions. Transgenic crops offer benefits such as improved stress tolerance, better recovery, stable productivity, and enhanced climate resilience, although they also face regulatory and public acceptance challenges.



Important Water-Efficient Crops

Crop	Important Traits
Sorghum	Deep roots and heat tolerance
Pearl millet	Excellent drought adaptation
Chickpea	Low water requirement
Pigeon pea	Efficient moisture use
Maize	Improved hybrid drought tolerance
Wheat	Drought-tolerant breeding lines
Rice	Alternate wetting and drought-tolerant varieties

Importance of Indigenous and Wild Germplasm

Wild crop relatives and indigenous landraces are important sources of drought-tolerance genes due to their rich genetic diversity and natural adaptation to harsh environments. These plants possess valuable traits such as stress

tolerance, climate adaptability, and resistance to pests and diseases. Scientists are increasingly studying desert plants and wild relatives to identify genes associated with water-use efficiency and improved stress resilience for future crop breeding programs.

Challenges in Breeding Water-Efficient Crops

Challenge	Explanation
Complex genetics	Drought tolerance is controlled by multiple genes
Environmental variation	Drought response differs across environments
Limited phenotyping	Difficult to measure drought traits accurately
Long breeding cycles	Development takes several years
Regulatory barriers	Gene-edited crops face policy issues
Farmer adoption	Awareness and accessibility challenges

Future Prospects

The future of water-efficient crop breeding depends on combining advanced technologies with sustainable agricultural practices. Emerging approaches such as CRISPR-based gene editing, AI-assisted breeding, pangenome analysis, precision agriculture, climate-smart farming, and speed breeding are accelerating the development of drought-resilient crops. Researchers are also focusing on perennial grain crops with deep root systems that improve water-use efficiency and soil sustainability. Due to increasing climate change risks and growing global food demand, investments in drought-resistant and water-efficient crop development are rapidly expanding worldwide.

the twenty-first century. Developing water-efficient crops is therefore essential for ensuring future food security, sustainable agriculture, and climate resilience. Modern breeding technologies including molecular breeding, genomics, artificial intelligence, phenomics, and gene editing are revolutionizing the development of drought-tolerant crop varieties. Water-efficient crops possess adaptive traits such as deep root systems, improved transpiration efficiency, osmotic adjustment, and enhanced stress tolerance mechanisms that enable better productivity under water-limited conditions. Advances in CRISPR technology, genomic selection, high-throughput phenotyping, and AI-driven breeding platforms are significantly accelerating crop improvement programs.

CONCLUSION

Water scarcity and climate change are among the greatest threats facing global agriculture in