

Research Perspective

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Advances in Water-Saving and High-Yield Cultivation Technologies for Winter Wheat under Climate Change

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Abstract Winter wheat is one of the major food crops in the world and plays an important role in ensuring global food security. However, extreme weather events and water shortages caused by climate change have created serious challenges for winter wheat production. The water demand of winter wheat changes greatly at different growth stages. Water demand is highest during the jointing-booting stage and grain filling stage, while the demand is relatively low during winter dormancy. Water deficit can cause stomatal closure and reduced transpiration, which further suppresses photosynthesis and accelerates leaf senescence. Combined high-temperature and drought stress can shorten the grain filling period and reduce thousand-grain weight. Improving water use efficiency (WUE) is the key to achieving both high yield and water saving. The rational use of deep soil water, efficient regulation of photosynthesis, and stress “memory” mechanisms can enhance the drought resistance of wheat. This study systematically reviews the physiological basis, cultivation technologies, and breeding progress of water-saving and high-yield cultivation of winter wheat under climate change conditions. It also discusses future development directions by combining digital agriculture and regional practices, providing references for coping with climate change and water resource crises.

Keywords Winter wheat; Water-saving cultivation; High yield; Climate change; Water use efficiency

1 Introduction

Winter wheat is one of the most important crops in the global food system and an important source of dietary energy and plant protein for people living in temperate agricultural regions. Compared with rice and maize, wheat has a wider adaptation range, more processing and utilization methods, and more active international trade. It plays an irreplaceable role in ensuring food security, stabilizing agricultural product supply, and maintaining the resilience of agricultural economies. Shiferaw et al. (2013) pointed out that wheat is not only an important staple food for people in developing countries, but also a key crop supporting agricultural livelihoods in many arid and semi-arid regions.

Rising temperatures, changes in the spatial and temporal distribution of precipitation, and the increasing occurrence of heat waves and drought events are changing the water–heat matching pattern in traditional winter wheat production areas (Jägermeyr et al., 2021). Especially in arid and semi-arid regions such as the North China Plain, northwest dryland areas, South Asia, and the Middle East, winter wheat often faces the contradiction between increased water demand during rapid spring growth and insufficient precipitation combined with enhanced evapotranspiration. Traditional irrigation methods have supported high wheat yields for a certain period, but they have also caused problems such as groundwater overexploitation, low irrigation efficiency, and intensified competition for agricultural water use. Improving water use efficiency has become an urgent goal in winter wheat production. The development of technologies such as remote sensing, unmanned aerial vehicles, and multi-angle spectral monitoring has also made dynamic monitoring of winter wheat water status and water use efficiency possible.

In actual production, high yield of winter wheat usually depends on sufficient water and nutrient supply, while water saving requires reducing irrigation frequency and total irrigation amount. This creates an internal contradiction between yield goals and resource limitations. Water-saving and high-yield production of winter wheat does not simply mean “less irrigation.” Instead, based on the water demand characteristics at different

growth stages, limited water resources should be preferentially allocated to key periods such as jointing, booting, flowering, and grain filling. At the same time, comprehensive measures are also needed, including soil moisture conservation, straw mulching, conservation tillage, coordinated water and fertilizer management, breeding of drought-resistant varieties, and precision irrigation decision-making (Liu et al., 2020).

Based on this background, this study mainly reviews the production problems, theoretical basis, and technical approaches of winter wheat under conditions of water resource limitation and increasing climate risk. The study analyzes the global importance of winter wheat production and the water stress problems caused by climate change, and explains the central role of improving water use efficiency in modern wheat production. In the future, winter wheat production should shift from traditional experience-based irrigation to precise diagnosis and intelligent decision-making, and from simply pursuing yield per unit area to the coordinated improvement of yield, water use efficiency, and ecological sustainability. This transition will help relieve pressure from water shortages and also provide references for stable yield improvement and efficiency enhancement of food crops under climate change.

2 Water Requirement Characteristics of Winter Wheat under Climate Change

2.1 Seasonal water requirement pattern

The water demand of winter wheat shows a clear seasonal pattern. From the seedling stage to the spring regreening stage, water consumption is relatively low because of low temperature and slow plant growth. During the winter dormancy period, water demand decreases further. After entering the jointing and booting stages in spring, rising temperatures and rapid vegetative growth cause water demand to increase quickly, usually reaching the highest level during the whole growth period. During the grain filling stage and late maturity stage, water demand decreases slightly but still remains relatively high to ensure grain filling and dry matter accumulation. Under strong light conditions and warm climates, the water requirement of winter wheat significantly increases around the heading stage. In late spring and early summer, especially during the late grain filling stage, plant transpiration gradually weakens. Water supply during key growth stages, particularly from jointing to flowering, is extremely important because water shortage during this period can significantly reduce yield. In regions such as the North China Plain, the average water requirement during the wheat growing season is about 400-500 mm, and more than 50% of the total water consumption occurs during the booting stage (Sun et al., 2024).

2.2 Physiological responses to water deficit

Under drought stress, wheat undergoes a series of physiological adjustments to adapt to water deficiency. In terms of stomatal regulation, drought stress increases the concentration of abscisic acid (ABA) in plants, which induces stomatal closure and reduces water loss through transpiration. However, stomatal closure also limits the entry of carbon dioxide, thereby suppressing photosynthesis. During short-term drought, stomatal closure is the main reason for reduced photosynthetic activity, while long-term and severe drought further downregulates genes related to photosynthetic metabolic pathways, causing additional damage to photosynthetic capacity (Li et al., 2023). Regarding transpiration, water shortage decreases leaf water potential and stomatal conductance, leading to a significant reduction in transpiration rate. Although this helps reduce water consumption, it also restricts nutrient transport within the plant. In addition, drought stress often causes oxidative stress because overload of the photosynthetic electron transport chain leads to the production of reactive oxygen species. Wheat improves cellular protection ability by increasing the activity of antioxidant enzymes such as peroxidase and superoxide dismutase, as well as accumulating osmotic adjustment substances including proline and betaine.

2.3 Effects of combined heat and drought stress

Climate change not only causes drought but also frequently leads to combined heat and drought stress. When high temperature occurs during the grain filling stage, the grain filling process is often accelerated and shortened, resulting in insufficient transfer of assimilates into grains and ultimately reducing thousand-grain weight. Under additional high-temperature conditions above 30 °C, the single-grain weight of spring wheat may decrease by 5%~12% (Wang et al., 2025). The combined effects of heat and drought can also intensify metabolic disorders in plants. Under water-deficient conditions aggravated by high temperature, stomata in wheat may close prematurely,

further affecting photosynthesis and accelerating leaf senescence, which eventually causes major yield reduction (Ye et al., 2024).

2.4 Water use efficiency under changing environmental conditions

Water Use Efficiency (WUE) is an important indicator for evaluating the water-saving production capacity of crops, and it can be assessed at both physiological and field levels. “Physiological WUE” usually refers to the ratio between CO₂ absorbed through photosynthesis and water lost through transpiration per unit leaf area (PN/Tr), reflecting the balance between photosynthetic efficiency and water loss under stomatal regulation. “Field WUE” refers to the dry matter yield or grain yield obtained per unit of crop water consumption (total evapotranspiration), commonly expressed as kg·ha⁻¹·mm⁻¹. Improvement of WUE can be achieved either by increasing yield or reducing water consumption. The use of modern water-saving irrigation methods and efficient cultivation technologies can significantly improve field WUE (Wu et al., 2025). Studies on winter wheat in northern China have shown that moderately reducing irrigation water combined with high-yield cultivation practices can increase WUE by more than 10% (Yang et al., 2025).

3 Physiological Basis of Water-Saving and High-Yield Cultivation

3.1 Root structure and utilization of deep soil water

The basis of water-saving and high-yield cultivation in winter wheat is not simply reducing water consumption above ground. More importantly, the root system must be able to convert limited soil water into effective grain yield under uneven spatial and temporal distribution of water. The growth period of winter wheat spans autumn, winter, spring, and summer. From regreening to grain filling, surface soil drought often occurs, while deeper soil layers may still retain water stored before winter or from earlier rainfall events.

Li et al. (2022) conducted two seasons of winter wheat pot experiments at the Luancheng Agro-Ecosystem Experimental Station on the North China Plain. Different soil depths of 0.5, 1.0, 1.5, and 2.0 m and water supply levels of 90~500 mm were established to simulate different rooting depths and soil water availability conditions. Under similar seasonal evapotranspiration, shallower root systems produced lower grain yield. Deep root systems not only increased the amount of available soil water, but also changed the distribution of water consumption during different growth stages, allowing more water to be used during reproductive growth. Deep roots improved “root efficiency,” meaning that higher grain production was achieved with lower root growth cost.

Odone et al. (2024) studied deep rooting traits of 14 winter wheat genotypes using the RadiMax semi-field root phenotyping platform in Denmark. Minirhizotrons reaching depths of 2.5 m were used to observe root growth, and water labeled with ¹⁵N and ²H was injected into soil layers at 1.6~1.8 m to determine whether deep roots actually functioned in absorption. Differences in deep root development were observed among winter wheat genotypes. Deep roots were associated with deep water uptake, nitrogen absorption, grain yield, and drought resistance. Genotypes with deeper roots showed larger reductions in water stress and greater yield increases when they could access deep soil layers. Therefore, drought resistance in winter wheat should not only be evaluated by plant height, leaf area, or spike number above ground, but also by deep rooting ability as an important trait for climate-adaptive breeding.

Sun et al. (2020) compared eight representative winter wheat cultivars grown in dryland areas of Shaanxi Province from the 1940s to the 2010s. Modern cultivars showed larger root surface areas under drought conditions, especially in the 0~40 cm soil layer. At the same time, grain yield significantly increased with cultivar improvement over decades, and water use efficiency increased by an average of 47.07% from early cultivars to modern cultivars. Long-term dryland breeding and cultivation selection did not simply produce “larger root systems,” but gradually achieved a more balanced coordination among root size, water uptake efficiency, and aboveground yield formation.

3.2 Regulation of photosynthesis under drought conditions

The effect of drought on winter wheat yield is ultimately reflected in reduced photosynthetic carbon assimilation and insufficient grain filling. Closure of leaf stomata can reduce water loss, but it also limits CO₂ entry into

mesophyll cells, leading to lower net photosynthetic rate. Under prolonged drought stress, chloroplast structure may be damaged, photosystem II electron transport may be inhibited, and reactive oxygen species may accumulate, causing premature leaf senescence.

Li et al. (2023) studied the effects of warming and drought stress on the coupling relationship between photosynthesis and transpiration in winter wheat on the North China Plain. Drought first reduced water loss by decreasing stomatal conductance. However, with increasing stress intensity, the decline in photosynthesis was no longer caused only by stomatal limitation, but also by downregulation of photosynthetic metabolism. In other words, mild water deficit may temporarily improve water use efficiency, but long-term or severe drought disrupts carbon-water coupling, turning water saving into yield reduction. Therefore, severe water deficit should be avoided during jointing, flowering, and early grain filling stages because photosynthetic capacity during these periods directly affects grain number and thousand-kernel weight.

During grain filling, the flag leaf is the major source of assimilates in late growth stages, and the duration of its photosynthetic activity directly affects grain fullness. Naseer et al. (2024) used the winter wheat cultivar “Xinong 979” in the dry farming region of the Loess Plateau to study the combined effects of drought and weak light during grain filling. Treatments included irrigation levels of 100%, 75%, 50%, and 25%, along with different shading durations. As irrigation decreased and shading time increased, net photosynthetic rate, transpiration rate, stomatal conductance, and intercellular CO₂ concentration all declined significantly. Under the treatment of 12 days of shading combined with the lowest irrigation level, photosynthetic gas exchange parameters showed the greatest decline. At the same time, chlorophyll fluorescence parameters Fv/Fm, qP, and quantum yield also decreased, indicating damage to PSII reaction centers (Figure 1). Drought and shading together reduced spike number, thousand-kernel weight, and grain yield, indicating that the grain filling stage is not simply a period where “less water is acceptable,” but rather a critical window when the photosynthetic system of winter wheat requires strong protection.

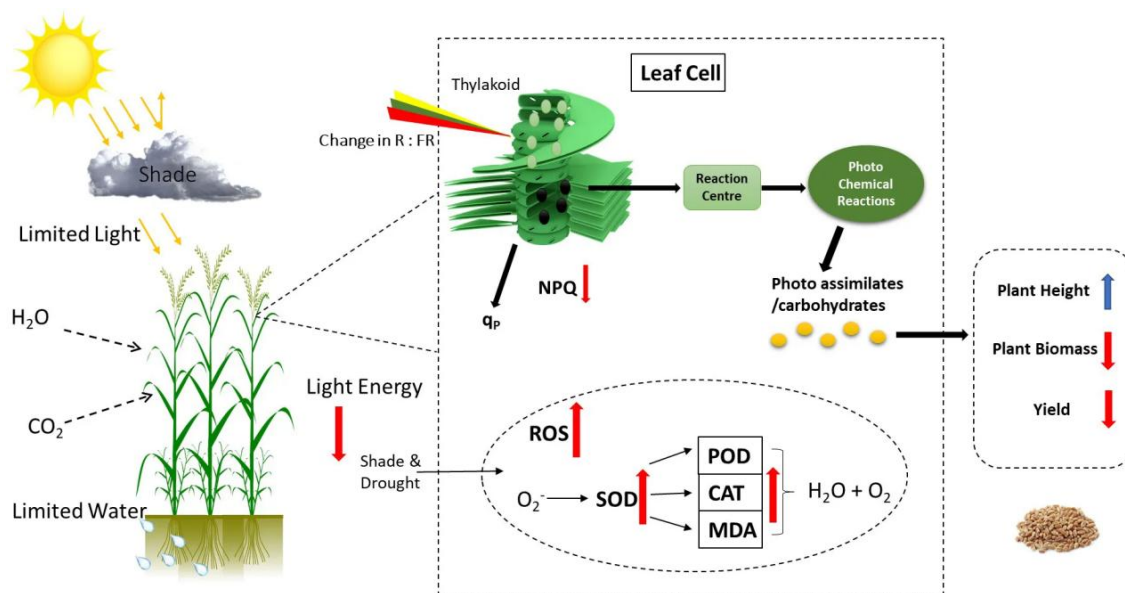


Figure 1 The comprehensive model of physiological metabolism regulation in winter wheat plants under drought and shading stress. Changing the light environment and drought conditions regulate the photosynthetic activity, photochemical efficacy, and antioxidant enzyme activities to adapt the environmental stress. The distribution and regulation of photo-assimilates affect the agronomic characteristics, and yield of winter wheat plants (Adopted from Naseer et al., 2024)

3.3 Water stress memory and adaptation mechanisms

Winter wheat has a certain capacity to adapt to water stress. Because the growth period is relatively long, winter wheat often experiences multiple stress events, including mild drought at the seedling stage, water fluctuations during regreening, spring drought after jointing, and hot dry wind during grain filling. If mild stress at early stages activates adaptive mechanisms, drought tolerance at later stages may be improved.

Amini et al. (2023) investigated drought stress memory in common wheat and synthetic wheat germplasm. Treatments included normal irrigation, secondary drought stress after seed priming, drought at jointing followed by severe drought at flowering, and single drought stress at flowering. A total of 27 wheat genotypes were evaluated. Plants exposed to moderate drought during jointing and then severe drought during flowering showed a more effective enzymatic antioxidant system, which reduced later yield loss. Clear differences in stress memory responses were found among genotypes, and synthetic wheat generally performed better than common wheat in grain yield, yield components, and drought resistance index. Changes in proline, soluble sugars, peroxidase, catalase, and ascorbate peroxidase under secondary stress indicated that osmotic adjustment and antioxidant defense are important physiological bases for stress memory formation in winter wheat.

3.4 Source-sink coordination during grain filling

The grain filling stage is the final critical period for yield formation in winter wheat and also the stage most vulnerable to yield risk under water-saving cultivation. The “source” mainly refers to assimilate-producing organs such as the flag leaf, the second leaf below the flag leaf, stems, and spikes, while the “sink” mainly refers to the grains.

Fang et al. (2024) quantitatively analyzed source-sink relationships using 13 years of semi-controlled field experiment data involving six bread wheat genotypes under combinations of high temperature, water deficit, and nitrogen deficiency. Across different environments and genotypes, grain biomass was on average about 10% higher than newly produced aboveground biomass after flowering. This indicates that grain filling does not rely entirely on newly formed photosynthates after anthesis, but also depends on remobilization of assimilates stored before flowering. More importantly, as stress intensity increased, the relative contribution of pre-anthesis assimilates to grain biomass increased from nearly 0 to 100%. This contribution was more strongly affected by water and nitrogen conditions than by temperature. Under drought or nitrogen deficiency, the ability of winter wheat to effectively transport previously accumulated carbohydrates into grains becomes the key factor determining grain filling stability.

On the Huang-Huai-Hai Plain of China, optimized irrigation can also improve source-sink relationships by delaying flag leaf senescence. Yan et al. (2023) reported in a two-year experiment that under traditional border irrigation, a border length of 40 m achieved a good balance between water saving and high yield. Compared with other border lengths, the L40 treatment enhanced antioxidant enzyme activity and sucrose metabolism in the flag leaf after flowering, delayed declines in SPAD value and chlorophyll fluorescence parameters, and promoted grain filling rate and thousand-kernel weight. In contrast, excessively short borders reduced yield, while excessively long borders lowered water productivity.

4 Advances in Water-Saving Cultivation Technology

4.1 Deficit irrigation strategies

Deficit irrigation (DI) is not simply reducing irrigation water input. Instead, it is a targeted regulation of irrigation timing, irrigation amount, and the lower limit of soil moisture according to the sensitivity of winter wheat to water deficit at different growth stages. From the regreening stage to jointing, winter wheat enters a period of rapid vegetative growth, with rapid expansion of leaf area and increased transpiration water consumption. The booting stage, flowering stage, and early grain-filling stage are directly related to spikelet number, grain formation, and dry matter transport to grains, so these stages require the greatest water guarantee in water-saving irrigation. In contrast, moderate water deficit during the overwintering stage, early regreening stage, or late maturity stage has relatively limited effects on final yield. Based on this, the concept of deficit irrigation has gradually formed: “moderate water control during non-critical periods and precise water supply during critical periods.”

From the perspective of regional irrigation systems, water-saving irrigation for winter wheat in the North China Plain emphasizes coordination with interannual precipitation differences. Optimal irrigation strategies differ among years with different rainfall conditions. In wet years, irrigation frequency can be reduced, and sometimes only one supplemental irrigation at flowering is enough. In normal rainfall years and dry years, two irrigations are generally required to balance water supply before and after flowering. The irrigation demand of winter wheat

varies greatly over multiple years, and irrigation water requirements may change significantly under different precipitation patterns. If irrigation is fixed without considering annual rainfall differences, water waste may occur in wet years, while water shortage may occur in dry years (Zhao et al., 2020).

The meta-analysis of irrigation-soil-climate interactions conducted by Yang et al. (2025) further explained the quantitative relationship between water saving and high yield. Many wheat irrigation experiments showed that irrigation significantly increased grain yield, spike number, grains per spike, and thousand-grain weight. However, the increase in water productivity was relatively limited because higher yield was accompanied by increased evapotranspiration. Irrigation amounts between 75 and 150 mm were more suitable for balancing grain yield and water productivity. When irrigation exceeded this range, the marginal yield increase gradually declined.

4.2 Precision irrigation technology

Traditional flood irrigation and furrow irrigation often have problems such as excessive irrigation amount, strong surface evaporation, deep percolation losses, and uneven soil water distribution. In contrast, drip irrigation, sprinkler irrigation, micro-sprinkler irrigation, and intelligent irrigation systems can improve the efficiency of water delivery to the root zone and reduce ineffective water consumption.

Yang et al. (2020) established five irrigation levels of 0.25, 0.40, 0.60, 0.80, and 1.00 ET_c in a subsurface drip irrigation experiment on winter wheat. Although the 0.25 and 0.40 ET_c treatments achieved obvious water savings, tiller number, leaf water content, leaf area index, net photosynthetic rate, and grain yield all decreased significantly. Compared with full irrigation, the 0.80 ET_c treatment showed only small differences in plant height, leaf area index, spike number, and photosynthetic-transpiration parameters, and could maintain yield relatively well. The 0.60 ET_c treatment showed a relatively high harvest index and water use efficiency. Deficit subsurface drip irrigation also promoted water extraction from the 40~140 cm soil layer, allowing crops to utilize more deep soil water storage.

Zheng et al. (2025) carried out a micro-sprinkler irrigation experiment in the North China Plain to compare the effects of different wetting depths and irrigation regimes on winter wheat yield, water productivity, and carbon emission efficiency. In years with normal rainfall, maintaining the wetting depth at 0~30 cm could sustain yield while reducing water consumption. In wet years, a wetting depth of 0~40 cm was more favorable for achieving high yield potential. Compared with drip irrigation, micro-sprinkler irrigation improved surface soil moisture distribution and, under certain conditions, reduced farmland CO₂ emission flux and improved carbon emission efficiency.

The value of intelligent irrigation systems lies in transforming “when to irrigate,” “how much to irrigate,” and “how deep to irrigate” into a calculable, monitorable, and feedback-based decision-making process. Soil moisture sensors, weather stations, UAV remote sensing, satellite remote sensing, and crop models have been integrated into irrigation management (Abdelhamid et al., 2025). Sun et al. (2024) used UAV hyperspectral technology to estimate leaf water content of winter wheat during the grain-filling stage and established the relationship between leaf water content and soil moisture to determine suitable irrigation amounts during grain filling. Since grain filling is a critical stage for grain formation, accurate evaluation of canopy water status helps improve both grain yield and water productivity. Compared with traditional soil sampling or experience-based observation, UAV monitoring has advantages such as high resolution, rapid coverage, and non-destructive measurement, making it suitable for field-scale water diagnosis (Figure 2).

4.3 Soil water conservation measures

For winter wheat, whether irrigation water can be effectively stored in soil, absorbed by roots, and protected from ineffective evaporation largely depends on tillage layer structure, straw mulching, soil organic matter, and soil porosity. If soil compaction is severe, the plow pan is thick, and infiltration capacity is poor, increasing irrigation may still result in surface runoff, deep leakage, or restricted root penetration.

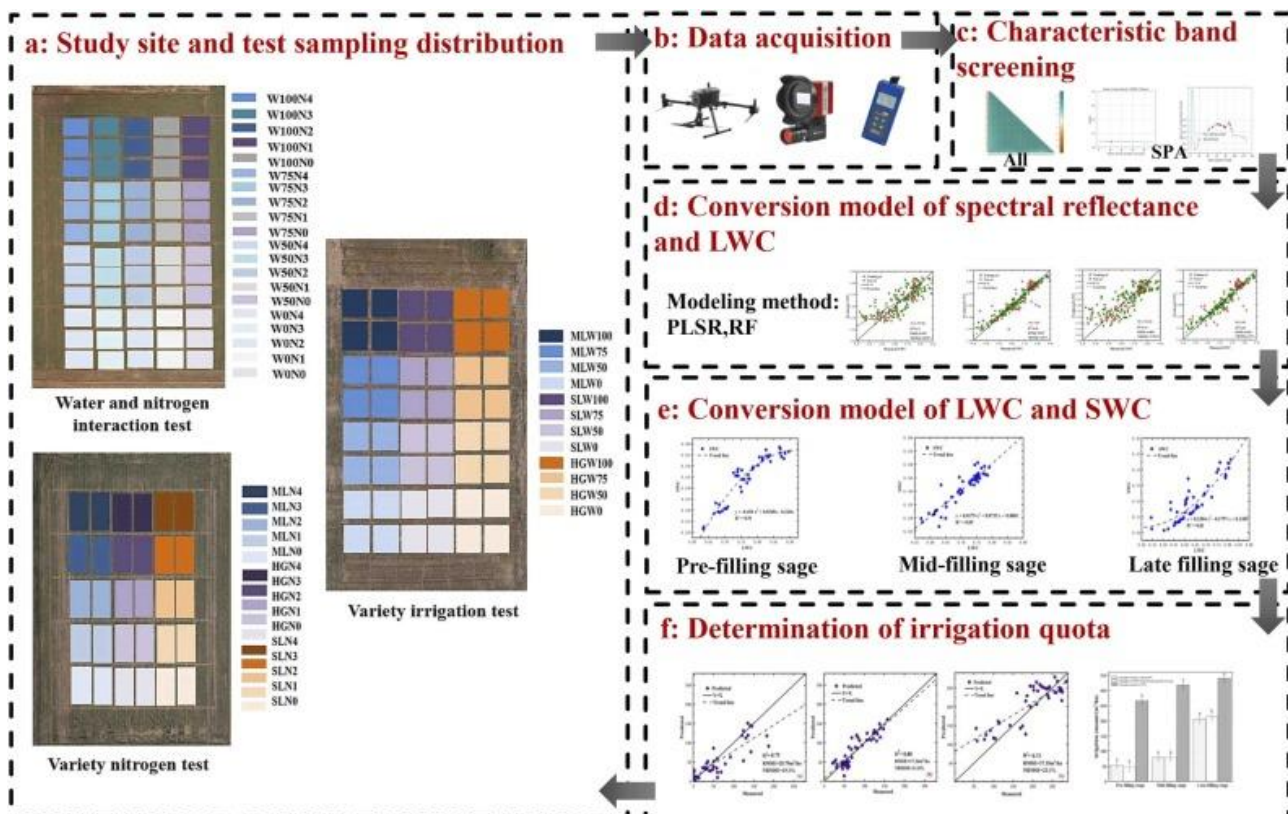


Figure 2 Test distribution and technical roadmap. Note: LWC, leaf water content; SWC, soil water content; PLSR, partial least squares regression; RF, random forest; ALL, hyperspectral band; SPA, successive projections algorithm (Adopted from Sun et al., 2024)

In dryland and semi-arid wheat systems, straw mulching can help retain more rainfall or irrigation water in the tillage layer and reduce evaporation losses from bare soil. Dong et al. (2025) studied the effects of long-term rotary tillage and straw mulching in a rainfed wheat-soybean rotation system. The results showed that appropriate tillage combined with straw management promoted dry matter accumulation, increased grain yield, and improved water use efficiency. Under unstable rainfall conditions, the role of straw mulching is not only to conserve soil moisture but also to influence final yield through improving crop growth and dry matter production.

Qiang et al. (2022) conducted field experiments in Xinxiang, Henan Province, comparing no-tillage, rotary tillage, and subsoiling combined with straw return in terms of tillage layer structure, grain yield, and WUE. Compared with no-tillage, subsoiling significantly reduced soil bulk density in the 20~40 cm layer, increased soil porosity, and reduced soil compaction in the 0~40 cm layer. Subsoiling combined with straw return also increased soil organic carbon in the tillage layer. More importantly, subsoiling promoted the downward movement of irrigation water and rainfall, creating a better soil environment for root growth. Compared with no-tillage, subsoiling increased winter wheat yield by 34.48%~38.10% and improved WUE by 19.57%~21.96%.

4.4 Integrated water and fertilizer management

Water and nutrients do not function independently. Water shortage limits nitrogen transport to the root zone and root absorption, while insufficient nitrogen supply weakens leaf area development, photosynthate accumulation, and root activity. Under water-saving conditions, reducing irrigation without adjusting fertilization can easily result in either “less water but excessive fertilizer” or “insufficient fertilizer efficiency.” On the other hand, simply increasing nitrogen fertilizer without improving water supply may increase the risk of nitrogen residue and leaching.

Wu et al. (2025) studied the effects of regulated deficit irrigation on winter wheat yield formation, water use efficiency, and nitrogen use efficiency under different soil fertility conditions. Regulated deficit irrigation was not

equally effective under all fertility levels. Under medium and low fertility conditions, moderate deficit irrigation improved WUE and partial factor productivity of nitrogen while maintaining or increasing grain yield. However, under high fertility conditions, regulated deficit irrigation could reduce grain yield or weaken nitrogen use efficiency.

5 Breeding and Genetic Improvement of Water-Saving Wheat

5.1 Drought-resistant germplasm resources

Drought resistance in wheat is not controlled by a single trait. It is determined by multiple characteristics together, including root water uptake ability, leaf water retention, stomatal regulation, osmotic adjustment, antioxidant capacity, early maturity for drought escape, and grain filling stability. In recent years, more attention has been paid to landraces, wild relatives, synthetic hexaploid wheat, and core germplasm resources preserved by international breeding institutions. Many countries and international gene banks have conserved a large number of wheat landraces and wild materials. During long-term natural selection and farmer selection, these materials gradually developed adaptation to drought, poor soils, heat stress, and other adverse environments (Khadka et al., 2020).

Common wheat experienced a genetic bottleneck during domestication and modern breeding. Some allelic variations related to drought resistance, deep rooting, and stress adaptation may have been weakened or lost. Synthetic hexaploid wheat is usually developed by crossing tetraploid durum wheat with D-genome donors such as *Aegilops tauschii*, followed by chromosome doubling. This approach allows favorable alleles from wild relatives to be reintroduced into the genetic background of common wheat. Rosyara et al. (2019) analyzed the genetic contribution of synthetic hexaploid wheat to CIMMYT spring bread wheat breeding materials and found that synthetic-derived lines had already entered the international wheat improvement system.

Mokhtari et al. (2022) evaluated 184 synthetic hexaploid wheat-derived lines under both normal irrigation and water stress conditions over two years. Large genetic variation was observed in agronomic traits such as plant height, heading date, spike traits, thousand-kernel weight, and grain yield. Under water stress, grain yield significantly decreased, but the degree of reduction differed greatly among genotypes, indicating that synthetic hexaploid derivatives contain valuable materials for drought improvement. Mokhtari et al. (2024) further screened drought-tolerant types from 91 synthetic hexaploid wheat lines. Under water stress, significant differences were observed in relative water content, leaf area index, photosynthetic pigments, proline accumulation, antioxidant enzyme activity, and malondialdehyde content. Some synthetic hexaploid materials maintained relatively high grain yield, higher leaf relative water content, and lower membrane lipid peroxidation under drought conditions.

5.2 Key genes related to drought resistance

Drought resistance in wheat involves many biological processes, including root development, water absorption, stomatal regulation, ABA signaling, reactive oxygen species scavenging, osmotic adjustment, and photosynthetic stability. In arid and semi-arid wheat-growing regions, water in the topsoil evaporates quickly, while deeper soil layers often still contain available moisture. Therefore, wheat lines with deeper root systems and higher deep-root density usually show more stable performance from stem elongation to grain filling stages.

When soil moisture decreases, ABA levels in roots and leaves increase. This induces stomatal closure to reduce transpiration and water loss, while also activating antioxidant systems, osmotic adjustment, and stress-response gene expression. Mega et al. (2019) showed that enhancing ABA receptor function could regulate water-use efficiency and drought resistance in wheat. They developed wheat materials overexpressing ABA receptors and found that total water consumption was reduced, while biomass production and grain yield per unit water increased. Mao et al. (2022) reported that wheat lines overexpressing TaPYL1-1B exhibited higher ABA sensitivity, stronger photosynthetic capacity, and higher water-use efficiency. Under water-deficit conditions, these lines showed improved drought tolerance and maintained grain yield. More importantly, the study identified a favorable allelic variation, TaPYL1-1Bn-442, in the promoter region of TaPYL1-1B. This variation contains a MYB recognition site that can be regulated by TaMYB70, thereby enhancing TaPYL1-1B expression in drought-tolerant genotypes (Figure 3).

In addition to ABA receptors, transcription factor genes are also important regulators of drought resistance in wheat. Chen et al. (2021) studied the wheat NAC transcription factor TaNAC48 and found that its expression was induced by drought, PEG treatment, hydrogen peroxide, and ABA. The gene was localized in the nucleus. Wheat lines overexpressing TaNAC48 showed higher proline content, lower water-loss rate, and reduced levels of malondialdehyde, hydrogen peroxide, and superoxide anions under drought stress. The study also demonstrated that TaAREB3 could bind to the ABRE element in the TaNAC48 promoter and activate its expression, revealing a regulatory relationship between ABA signaling and NAC transcription factors.

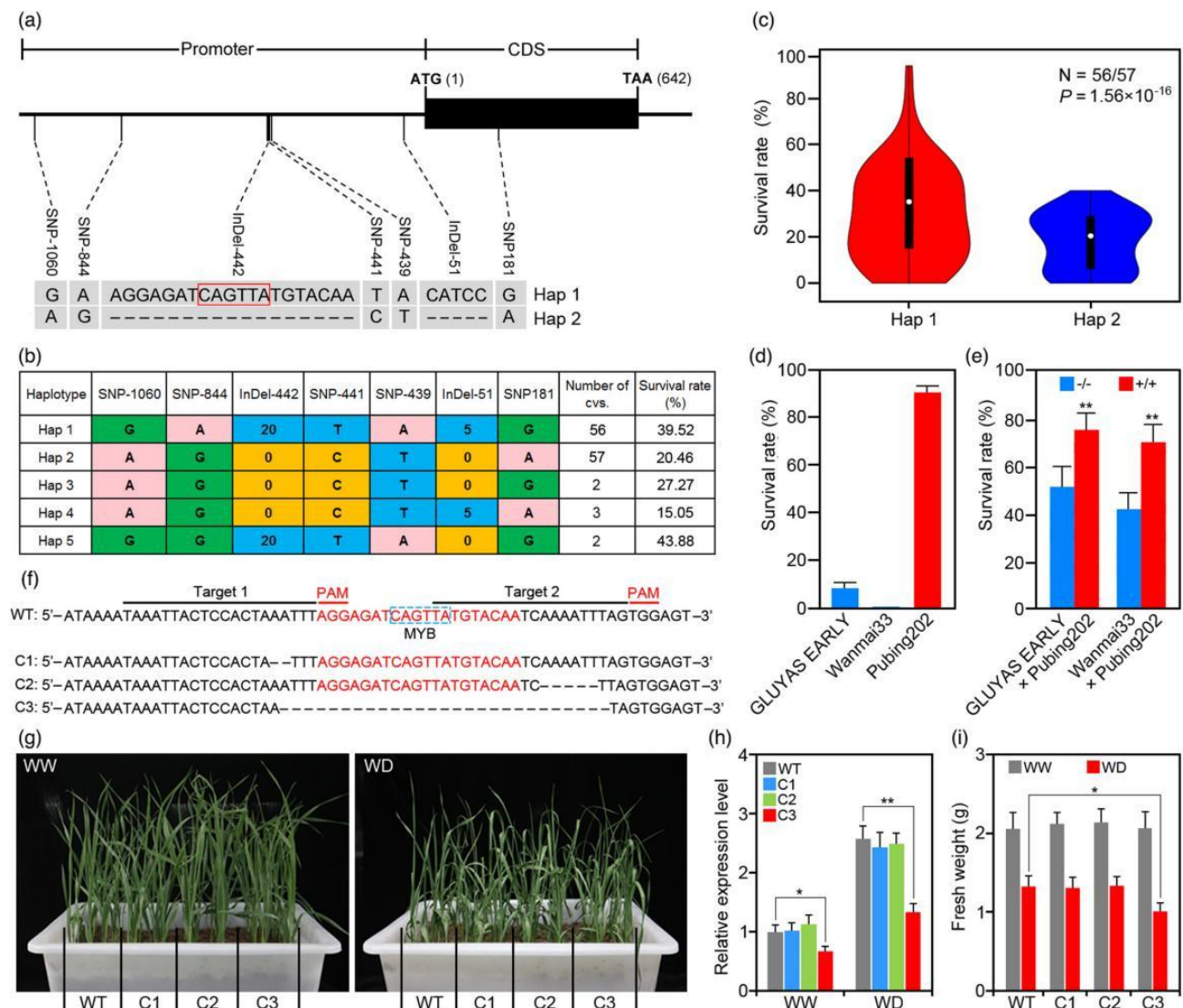


Figure 3 Genetic variations in TaPYL1-1B and their association with wheat drought tolerance (a) Distribution of DNA polymorphisms within the TaPYL1-1B promoter and the coding sequence region. The red frame indicates an MYB-binding sequence. (b) Haplotype analysis of TaPYL1-1B genotypes among 120 wheat varieties based on seven SNPs/indels. (c) Comparison of drought tolerance between wheat varieties carrying Hap 1 and Hap 2 genotypes. (d) Survival rates of wheat cv. Pubing202, Wanmai33 and GLUYAS EARLY plants under severe drought stress. (e) The survival rates of the F4 individuals carrying either the homozygous tolerant (+/+) or sensitive (-/-) allele of TaPYL1-1B in response to drought conditions. (f) Targeted mutagenesis of the 20-bp insertion via CRISPR-Cas9. Red labels indicate protospacer adjacent motif (PAM) sequences. Three independent lines were obtained harbouring deletions of the 20-bp insertion or its flanking sequence. (g) Phenotypic analysis of drought tolerance and (h) TaPYL1-1B relative expression levels in deletion mutants and WT plants under well-watered (WW) and water-deficit (WD) conditions. (i) Fresh weight of mutant and WT plants under WW and WD conditions. Data represent the mean ± SD of three replicates. Statistical significance was determined by a Student's t test, * P < 0.05; ** P < 0.01 (Adopted from Mao et al., 2022)

5.3 Marker-assisted selection and genomic breeding

Since drought resistance in wheat is controlled by multiple genes and is strongly influenced by environmental conditions, field phenotypic selection alone is easily affected by differences in year, soil, and management practices. The advantage of marker-assisted selection is that early-generation selection can be carried out around identified QTLs or candidate genes, reducing uncertainty in breeding. Genomic selection uses high-density genome-wide markers to predict breeding values and is more suitable for complex quantitative traits such as grain yield, water-use efficiency, canopy temperature, heading date, and grain filling stability. Nouraei et al. (2024) conducted a genome-wide association study on drought resistance in wheat and identified loci and candidate genes associated with drought tolerance using SNP markers.

The CIMMYT wheat breeding system adopted genomic selection relatively early for grain yield and adaptation improvement. Juliana et al. (2020) systematically analyzed the application of genomic selection for grain yield in the CIMMYT wheat breeding program. They pointed out that genomic selection can use marker information to predict yield potential in early-generation materials, shorten the breeding cycle, and identify stable high-yield lines across multiple environments. This is particularly important for drought resistance and water-saving breeding because water-stress experiments are costly, environmental variation is large, and repeated evaluations require long periods. Genomic prediction can therefore improve screening efficiency.

5.4 Gene editing and future climate-smart wheat

Traditional breeding requires hybridization, backcrossing, and many years of selection to combine favorable alleles, resulting in a relatively long breeding cycle. In contrast, the CRISPR/Cas system can achieve targeted mutation, knockout, base substitution, or expression regulation in specific genes or regulatory regions, making it suitable for precise improvement of genes with known functions. For hexaploid common wheat, gene editing is especially valuable because many genes have three homologous copies in the A, B, and D genomes. Traditional mutant screening makes it difficult to obtain functional changes in all copies simultaneously, whereas CRISPR can edit multiple homologous genes at the same time, improving both functional validation and trait improvement efficiency.

At present, drought-related gene editing in wheat is still moving from functional verification toward breeding application. Zhao et al. (2024), in their study on CRISPR/CasΦ2-mediated gene editing in wheat and rye, showed that new Cas systems are expanding the wheat gene-editing toolbox. The significance of these tools is not only that they can perform editing, but also that they may allow combined regulation of multiple drought-resistance pathways in the future.

6 Digital Agriculture and Smart Water Resource Management

6.1 Remote sensing and soil moisture monitoring

Remote sensing technology uses satellites or drones to collect land cover, vegetation index, and soil information, providing an effective way to evaluate crop growth and monitor water conditions over large agricultural areas (Zhang et al., 2021). Multispectral data from Sentinel-2, Landsat, and similar platforms can be used to estimate crop chlorophyll content and evapotranspiration through Land Surface Temperature analysis, which helps indirectly estimate soil moisture conditions. At the same time, more small soil moisture sensors are being installed in farmland, and these sensors can upload underground moisture data in real time through wireless networks. By combining these data with machine learning models, researchers and farmers can predict field water demand and carry out precise irrigation scheduling. Drone remote sensing has high spatial resolution and strong flexibility, so it is widely used in stress testing and drought diagnosis for local wheat fields.

6.2 Artificial intelligence-based irrigation decision systems

Deep learning models can integrate meteorological data, remote sensing images, and soil sensor information to predict crop water demand trends. Water resource management frameworks that combine satellite remote sensing and deep learning can improve the prediction accuracy of soil moisture and irrigation demand to more than 90%. In wheat irrigation research, algorithms such as Convolutional Neural Networks (CNN) and Long Short-Term Memory networks (LSTM) have already been tested for water demand prediction and water-saving irrigation

planning. In addition, reinforcement learning and intelligent optimization algorithms are also used to automatically regulate valves and pumping stations in response to changing field water conditions in real time. Some smart irrigation systems continuously improve their performance through reinforcement learning trial-and-error processes, making it possible to reduce water use while maintaining crop health.

6.3 Application of the internet of things in wheat production

By deploying sensor networks, it is possible to monitor temperature, humidity, soil moisture, and soil nutrients in real time, and the collected data can be transmitted wirelessly to control centers (Jawad et al., 2017). Sensor arrays combined with satellite communication technology allow real-time monitoring of soil moisture in remote farms. Automatic irrigation control systems can operate without direct human supervision. When sensors detect that soil moisture falls below a set threshold, pumps automatically start irrigation, and the pumps shut down automatically after irrigation is completed. Compared with traditional manual irrigation, automated systems reduce human error and improve irrigation accuracy. Some smart irrigation gateways can even use edge computing to run simple decision-making models directly in the field, which further reduces response time.

6.4 Big data and predictive agriculture

Short-term and long-term weather forecasts, drought indexes, and related information provided by meteorological agencies and research institutions can serve as the basis for preparing irrigation plans in advance. By mining historical yield, soil, and climate data, prediction models for crop yield and water demand can be established to support farmer decision-making. For example, long-term experimental data show that the occurrence probability of heat stress in wheat is closely related to crop yield, which can help estimate harvest risks and guide timely adjustments in planting density or irrigation strategies. In terms of water resource allocation, decision-makers can combine hydrological forecasts with crop water demand models to distribute limited water resources, such as groundwater and river water, more scientifically for regional water conservation. Climate warning systems, including drought early warning systems, can also provide guidance for spring sowing plans and water-saving irrigation measures. Big data-based decision support systems are gradually becoming more common, making wheat production more forward-looking and adaptable.

7 Challenges and Future Prospects

7.1 Balancing yield stability and water saving

Under conditions of limited resources, balancing grain yield and water use efficiency remains a major challenge. Excessive pursuit of maximum yield usually depends on large amounts of irrigation, while overly strict irrigation restriction may lead to yield reduction. Future studies should seek a compromise between physiological mechanisms and system optimization. Breeding wheat genotypes with high photosynthetic efficiency and high WUE, combined with moderate deficit irrigation strategies (such as 75% ET_c), may help achieve the goal of “moderate stress and efficiency priority” (Wu et al., 2025). At the same time, regional differences should also be considered. For example, winter wheat in southern regions generally requires more water and can rely on rainfall supplementation, while northern arid areas should focus more on soil moisture conservation and the use of drought-tolerant cultivars.

7.2 Climate uncertainty and extreme weather risks

Global warming has increased uncertainty in agricultural production. High-temperature heatwaves and long-term drought events are becoming more common and are now major factors affecting wheat yield. To cope with climate risks, it is necessary to improve the resilience of agricultural systems. This includes establishing drought early-warning systems, adjusting sowing dates and cultivar selection more flexibly, and promoting stress-resistant wheat varieties. For example, planting plans can be developed with the support of multi-model climate simulations. If a heatwave is predicted during flowering, early-maturing and heat-tolerant cultivars can be used to reduce production risks. In addition, “insurance-based agriculture” and regulation mechanisms, such as water storage reservoirs and subsidy policies, can help reduce risks for farmers. Agricultural production systems should also become more flexible. In double-cropping systems, adjusting planting density according to climate conditions can partly offset losses caused by extreme weather.

7.3 Limitations of current irrigation technologies

Although many water-saving technologies have been developed, there are still several difficulties in practical application. First, advanced irrigation equipment, such as intelligent irrigation systems, is expensive and difficult for small-scale farmers to adopt without policy support and financial subsidies. Second, natural resource conditions vary greatly among regions, and the same technology may produce different effects in different environments. Therefore, localized technical evaluation is necessary. In addition, agricultural information services and technology extension systems still need improvement. Limited farmer training and low acceptance of new technologies have slowed down the adoption process. For example, the deployment rate of intelligent irrigation systems remains low in some areas of North China, while traditional farming habits in arid regions of Northwest China also limit the promotion of improved cultivation practices. Finally, more accurate decision-support tools are still needed. Many existing AI models cannot fully simulate the complete growth process of wheat, and more practical and adaptable agronomic models should be further developed.

7.4 Future development directions of climate-smart wheat systems

In the future, the trends of “smart agriculture” and “low-carbon agriculture” will strongly influence winter wheat production systems. In smart agriculture, technologies such as 5G communication, edge computing, and artificial intelligence will be more widely applied, allowing the whole crop production process to become digitalized. Every stage, from sowing to harvesting, can be monitored through cloud-based systems. Drone pesticide spraying and automated agricultural robots may become common practices. At the same time, new sensors, such as miniature UAV multispectral sensors, will enable real-time monitoring of microclimate conditions and vegetation indicators.

Biotechnology will also contribute to water management. For example, engineered microorganisms may regulate rhizosphere environments and improve water absorption, while symbiotic microbes may enhance soil water retention capacity. Regenerative agricultural systems, including cover crop strip farming and mixed cropping, can improve soil structure and regional water cycles, thereby indirectly increasing WUE. In addition, under the background of greenhouse gas reduction, low-carbon agricultural practices will gradually be introduced into wheat production systems. Energy-saving irrigation methods, such as solar-powered pumps and drip or micro-sprinkler irrigation systems, can reduce fossil fuel consumption. Overall, future wheat production systems will integrate information technology, mechanization, and biotechnology, gradually developing toward climate-smart agriculture to achieve sustainable high yield and water-saving goals.

Author Contributions

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Reference

- Abdelhamid M.A., Abdelkader T.K., Sayed H.A.A., Zhang Z., Zhao X., and Atia M.F., 2025, Design and evaluation of a solar powered smart irrigation system for sustainable urban agriculture, *Scientific Reports*, 15(1): 11761.
<https://doi.org/10.1038/s41598-025-94251-3>
- Amini A., Majidi M.M., Mokhtari N., and Ghanavati M., 2023, Drought stress memory in a germplasm of synthetic and common wheat: antioxidant system, physiological and morphological consequences, *Scientific Reports*, 13(1): 8569.
<https://doi.org/10.1038/s41598-023-35642-2>
- Chen J., Gong Y., Gao Y., Zhou Y., Chen M., Xu Z., Guo C., and Ma Y., 2021, TaNAC48 positively regulates drought tolerance and ABA responses in wheat (*Triticum aestivum* L.), *The Crop Journal*, 9(4): 785-793.
<https://doi.org/10.1016/j.cj.2020.09.010>
- Dong S., Huang M., Zhang J., Zhou Q., Hu C., Liu A., Wang H., Fu G., Wu J., and Li Y., 2025, Long-term rotary tillage and straw mulching enhance dry matter production, yield, and water use efficiency of wheat in a rain-fed wheat-soybean double cropping system, *Plants*, 14(15): 2438.
<https://doi.org/10.3390/plants14152438>

- Fang L., Struik P.C., Girousse C., Yin X., and Martre P., 2024, Source-sink relationships during grain filling in wheat in response to various temperature, water deficit, and nitrogen deficit regimes, *Journal of Experimental Botany*, 75(20): 6563-6578.
<https://doi.org/10.1093/jxb/erae310>
- Jägermeyr J., Müller C., Ruane A.C., Elliott J., Balkovic J., Castillo O., Faye B., Foster I., Folberth C., Franke J.A., Fuchs K., Guarín J.R., Heinke J., Hoogenboom G., Iizumi T., Jain A.K., Kelly D., Khabarov N., Lange S., Lin T.S., Liu W.F., Mialyk O., Minoli S., Moyer E.J., Okada M., Phillips M., Porter C., Rabin S.S., Scheer C., Schneider J.M., Schyns J.F., Skalsky R., Smerald A., Stella T., Stephens H., Webber H., Zabel F., and Rosenzweig C., 2021, Climate impacts on global agriculture emerge earlier in new generation of climate and crop models, *Nature Food*, 2(11): 873-885.
<https://doi.org/10.1038/s43016-021-00400-y>
- Jawad H.M., Nordin R., Gharghan S.K., Jawad A.M., and Ismail M., 2017, Energy-efficient wireless sensor networks for precision agriculture: A review, *Sensors*, 17(8): 1781.
<https://doi.org/10.3390/s17081781>
- Juliana P., Singh R.P., Braun H.J., Huerta-Espino J., Crespo-Herrera L., Govindan V., Mondal S., Poland J., and Shrestha S., 2020, Genomic selection for grain yield in the CIMMYT wheat breeding program-Status and perspectives, *Frontiers in Plant Science*, 11: 564183.
<https://doi.org/10.3389/fpls.2020.564183>
- Khadka K., Raizada M.N., and Navabi A., 2020, Recent progress in germplasm evaluation and gene mapping to enable breeding of drought-tolerant wheat, *Frontiers in Plant Science*, 11: 1149.
<https://doi.org/10.3389/fpls.2020.01149>
- Li H., Li L., Liu N., Chen S., Shao L., Sekiya N., and Zhang X., 2022, Root efficiency and water use regulation relating to rooting depth of winter wheat, *Agricultural Water Management*, 269: 107710.
<https://doi.org/10.1016/j.agwat.2022.107710>
- Li Q., Gao Y., Hamani A.K.M., Fu Y., Liu J., Wang H., and Wang X., 2023, Effects of warming and drought stress on the coupling of photosynthesis and transpiration in winter wheat (*Triticum aestivum* L.), *Applied Sciences*, 13(5): 2759.
<https://doi.org/10.3390/app13052759>
- Liu Y.M., Liu D.Y., Zhao Q.Y., Zhang W., Chen X.X., Xu S.J., and Zou C.Q., 2020, Zinc fractions in soils and uptake in winter wheat as affected by repeated applications of zinc fertilizer, *Soil and Tillage Research*, 200: 104612.
<https://doi.org/10.1016/j.still.2020.104612>
- Mao H., Jian C., Cheng X., Chen B., Mei F., Li F., Zhang Y., Li S., Du L., Li T., Hao C., Wang X., Zhang X., and Kang Z., 2022, The wheat ABA receptor gene TaPYL1-1B contributes to drought tolerance and grain yield by increasing water-use efficiency, *Plant Biotechnology Journal*, 20(5): 846-861.
<https://doi.org/10.1111/pbi.13764>
- Mega R., Abe F., Kim J.S., Tsuboi Y., Tanaka K., Kobayashi H., Sakata Y., Hanada K., Tsujimoto H., Kikuchi J., Cutler S.R., and Okamoto M., 2019, Tuning water-use efficiency and drought tolerance in wheat using abscisic acid receptors, *Nature Plants*, 5(2): 153-159.
<https://doi.org/10.1038/s41477-019-0361-8>
- Mokhtari N., Majidi M.M., and Mirolohi A., 2022, Potentials of synthetic hexaploid wheats to improve drought tolerance, *Scientific Reports*, 12(1): 20482.
<https://doi.org/10.1038/s41598-022-24678-5>
- Mokhtari N., Majidi M.M., and Mirolohi A., 2024, Physiological and antioxidant responses of synthetic hexaploid wheat germplasm under drought, *BMC Plant Biology*, 24(1): 747.
<https://doi.org/10.1186/s12870-024-05445-2>
- Naseer M.A., Hussain S., Mukhtar A., Rui Q., Ru G., Ahmad H., Zhang Z.Q., Shi L.B., Asad M.S., Chen X.L., Zhou X.B., and Ren X., 2024, Chlorophyll fluorescence, physiology, and yield of winter wheat under different irrigation and shade durations during the grain-filling stage, *Frontiers in Plant Science*, 15: 1396929.
<https://doi.org/10.3389/fpls.2024.1396929>
- Nouraei S., Mia M.S., Liu H., Turner N.C., and Yan G., 2024, Genome-wide association study of drought tolerance in wheat (*Triticum aestivum* L.) identifies SNP markers and candidate genes, *Molecular Genetics and Genomics*, 299(1): 22.
<https://doi.org/10.1007/s00438-024-02104-x>
- Odone A., Popovic O., and Thorup-Kristensen K., 2024, Deep roots: implications for nitrogen uptake and drought tolerance among winter wheat cultivars, *Plant and Soil*, 500(1): 13-32.
<https://doi.org/10.1007/s11104-023-06255-5>
- Rosyara U., Kishii M., Payne T., Sansaloni C.P., Singh R.P., Braun H.J., and Dreisigacker S., 2019, Genetic contribution of synthetic hexaploid wheat to CIMMYT's spring bread wheat breeding germplasm, *Scientific Reports*, 9(1): 12355.
<https://doi.org/10.1038/s41598-019-47936-5>
- Shiferaw B., Smale M., Braun H.J., Duveiller E., Reynolds M., and 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(3): 291-317.
<https://doi.org/10.1007/s12571-013-0263-y>
- Sun X., Zhang B., Dai M., Jing C., Ma K., Tang B., Li K., Dang H., Gu L., Zhen W., and Gu X., 2024, Accurate irrigation decision-making of winter wheat at the filling stage based on UAV hyperspectral inversion of leaf water content, *Agricultural Water Management*, 306: 109171.
<https://doi.org/10.1016/j.agwat.2024.109171>

- Sun Y., Zhang S., and Chen W., 2020, Root traits of dryland winter wheat (*Triticum aestivum* L.) from the 1940s to the 2010s in Shaanxi Province, China, Scientific Reports, 10(1): 5328.
<https://doi.org/10.1038/s41598-020-62170-0>
- Wang K., Liu H., Zhou X., and Tang X., 2025, Comprehensive mega-data analysis of water use efficiency in winter wheat and its influencing factors, Water, 17(4): 564.
<https://doi.org/10.3390/w17040564>
- Wu X., Huang Z., Huang C., Liu Z., Liu J., Cao H., and Gao Y., 2025, Regulated deficit irrigation improves yield formation and water and nitrogen use efficiency of winter wheat at different soil fertility levels, Agronomy, 15(8): 1874.
<https://doi.org/10.3390/agronomy15081874>
- Yan F., Yu Z., and Shi Y., 2023, Optimized border irrigation delays winter wheat flag leaf senescence and promotes grain filling, Frontiers in Plant Science, 14: 1051323.
<https://doi.org/10.3389/fpls.2023.1051323>
- Yang M.D., Leghari S.J., Guan X.K., Ma S.C., Ding C.M., Mei F.J., Wei L., and Wang T.C., 2020, Deficit subsurface drip irrigation improves water use efficiency and stabilizes yield by enhancing subsoil water extraction in winter wheat, Frontiers in Plant Science, 11: 508.
<https://doi.org/10.3389/fpls.2020.00508>
- Yang Y., Wang Z., Ma Y., Wang Y., Bai J., and Zhang R., 2025, Balancing yield and water productivity in wheat: A meta-analysis of irrigation, soil, and climate interactions, Agricultural Water Management, 322: 109999.
<https://doi.org/10.1016/j.agwat.2025.109999>
- Ye Z., Yin S., Cao Y., and Wang Y., 2024, AI-driven optimization of agricultural water management for enhanced sustainability, Scientific Reports, 14(1): 25721.
<https://doi.org/10.1038/s41598-024-76915-8>
- Zhang H.Y., Liu M.R., Feng Z.H., Song L., Li X., Liu W.D., Wang C.Y., and Feng W., 2021, Estimations of water use efficiency in winter wheat based on multi-angle remote sensing, Frontiers in Plant Science, 12: 614417.
<https://doi.org/10.3389/fpls.2021.614417>
- Zhao J., Han T., Wang C., Jia H., Worqlul A.W., Norelli N., Zeng Z., and Chu Q., 2020, Optimizing irrigation strategies to synchronously improve the yield and water productivity of winter wheat under interannual precipitation variability in the North China Plain, Agricultural Water Management, 240: 106298.
<https://doi.org/10.1016/j.agwat.2020.106298>
- Zhao S., Han X., Zhu Y., Han Y., Liu H., Chen Z., Li H., Wang D., Tian C., Yuan Y., Guo Y., Si X., Wang D., and Ji X., 2024, CRISPR/CasΦ2-mediated gene editing in wheat and rye, Journal of Integrative Plant Biology, 66(4): 638-641.
<https://doi.org/10.1111/jipb.13624>
- Zheng H., Zheng C., Sun C., Zheng Y., Cao C., Zhang A., Zhang J., and Dang H., 2025, Micro-sprinkler irrigation with optimal irrigation regimes maintain grain yields while increasing carbon emission efficiency and water productivity of winter wheat on the North China Plain, Agricultural Water Management, 321: 109933.
<https://doi.org/10.1016/j.agwat.2025.109933>
- Zhou Y., Wang D., Wang H., Qiao Y., Zhao P., Cao Y., Liu X., Yang Y., Lin X., Xu S., Dong B., and Xiao J., 2025, Integrative omics of the genetic basis for wheat WUE and drought resilience reveal the function of TaMYB7-A1, Nature Communications, 16(1): 8622.
<https://doi.org/10.1038/s41467-025-63642-5>



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