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 CO_2 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 $kg \cdot ha^{-1} \cdot mm^{-1}$. 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 ^{15}N and ^{2}H 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 CO_2 entry into