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 ℃, 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,