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