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 ETc in a subsurface drip irrigation experiment on winter wheat. Although the 0.25 and 0.40 ETc 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 ETc 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 ETc 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 CO_2 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.