Water availability also interacts with density and N to determine canopy architecture and uniformity. Under limited irrigation, increasing seeding density can maintain grain yield while markedly improving water productivity by boosting spike number per unit area and canopy apparent photosynthesis in upper layers (Figure 1) (Gao et al., 2021). Optimal combinations of irrigation and N (e.g., irrigation at jointing and anthesis with moderate N) increase spike number, grains per spike, leaf area index, and canopy photosynthesis, while a well-distributed root system supports better extraction of soil water and coordinates root-shoot balance (Wang et al., 2025). Conversely, overly sparse or heterogeneous water distribution in drip systems can create non-uniform subpopulations with reduced leaf area, biomass, and panicle number in disadvantaged rows, lowering overall yield (Jing et al., 2023).

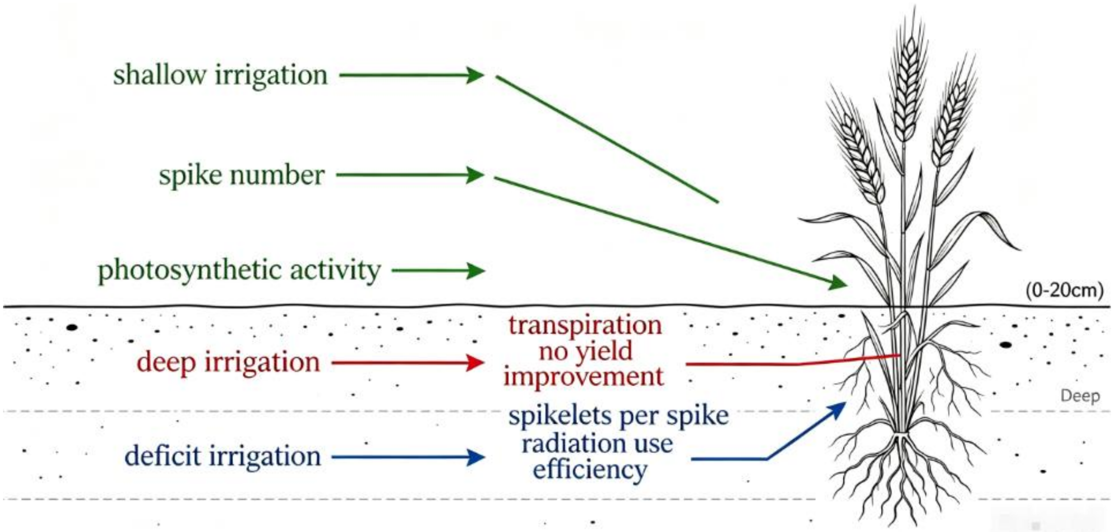

Figure 1 Mechanistic effects of irrigation depth and timing on tiller survival, spike formation, and yield component development in wheat

2.3 Response mechanisms of planting density and crop competition

Planting density regulates the balance between individual plant growth and population yield through intraspecific competition. As density increases, competition intensity rises, leading to reduced tillering, individual biomass, and grain number per plant, but greater spike number per area and, up to an optimum, higher population yield. In high-resource environments, winter wheat can reach near-maximum yields at surprisingly low plant densities, indicating strong compensatory capacity via tillering and spike fertility when competition is relaxed (Lollato et al., 2024). Reviews and field trials show that excessive seeding ultimately depresses yield components and grain yield due to self-thinning and resource limitation, underscoring the need for an optimum rather than maximal density (Arshad et al., 2025).

Competition also drives physiological and structural adjustments. High density often increases shoot elongation while reducing leaf mass per area, tiller number, and per-stem biomass, reflecting shade-avoidance and resource partitioning among competing plants. Breeding trajectories show decreasing shoot competitiveness indices over time, consistent with selecting genotypes that cooperate better at high density by limiting aggressive competitive traits (Manntschke et al., 2025). Experiments combining density with N show that raising density while moderating N can favor superior tillers, optimize spike number, and improve nitrogen-use efficiency, whereas very high N at high density mainly inflates vegetative growth and reduces partial factor productivity (Yang et al., 2019). Together, these mechanisms illustrate that planting density, competition, and genotype jointly determine how yield components respond under intensive management.

3 Dynamic Patterns of Wheat Yield Component Formation

3.1 Temporal characteristics of spike number formation

Spike number in wheat is largely determined by the production and survival of tillers over a defined developmental window from early vegetative stages to anthesis. Studies show that most fertile spikes originate