environmental effects on leaf area, chlorophyll, and biomass during the filling period and can therefore serve as a sensitive indicator of how management practices buffer or amplify climatic stresses.

4 Yield Variations Driven by Management Practices

4.1 Yield responses under different fertilization strategies

Nitrogen rate and timing strongly regulate wheat yield by altering spike number, grain number, and grain weight. Split spring N in winter wheat mainly increased spikes·m^{-2}, with yields peaking when 100 kg·N·ha^{-1} was applied early (BBCH 22-25) and 40 kg·ha^{-1} at stem elongation, reflecting the importance of early N for productive shoot survival (Lachutta and Jankowski, 2024). Across small grains, grain number per unit area is the key driver of yield, and high N (e.g., 100 kg·N) markedly increases grain number and grain yield, although trade-offs with grain weight can occur (Mirosavljević et al., 2025).

Yield responses to N show clear optima rather than linear increases. In semiarid Loess Plateau conditions, higher N rates (e.g., 210 kg·ha^{-1}) maximized yield in wet years, while intermediate N (150 kg·ha^{-1}) was optimal in normal or dry years, indicating precipitation-dependent N demand (Ren et al., 2021). Detailed dose-response studies further show that 210-240 kg·N·ha^{-1} can maximize spike number, grains per ear, thousand-grain weight and grain yield, whereas excessive N (300 kg·ha^{-1}) reduces spike grains and does not improve yield (Qu et al., 2025).

4.2 Yield differences under varying irrigation conditions

Irrigation strategy and amount substantially modify yield level and resource efficiency. Under sprinkler irrigation, full conventional irrigation (CI100) gave the highest grain yield, while a slight reduction (CI75) maintained high yield and increased water use efficiency, indicating that moderate deficit can save water with limited yield loss (Alghory and Yazar, 2018). In drip-fertigated systems, deficit irrigation at 75% ETc combined with moderate N (170 kg·ha^{-2}) produced the highest yields and water- and N-use efficiency, with most of the yield gain attributed to N but a sizeable portion to irrigation (Lu et al., 2021).

Timing of supplemental irrigation is also critical. In North China Plain field trials, irrigation at jointing and anthesis optimized root distribution, post-anthesis dry matter accumulation, and grain filling, increasing grain yield and water use efficiency compared with no irrigation or excessive frequency (Figure 2) (Feng et al., 2023). In Mediterranean durum wheat, two irrigations at flowering and grain filling raised grain yield by about 19-46% and increased thousand-kernel weight relative to rainfed conditions, demonstrating strong benefits of relieving post-flowering drought (Mohammadi, 2024).

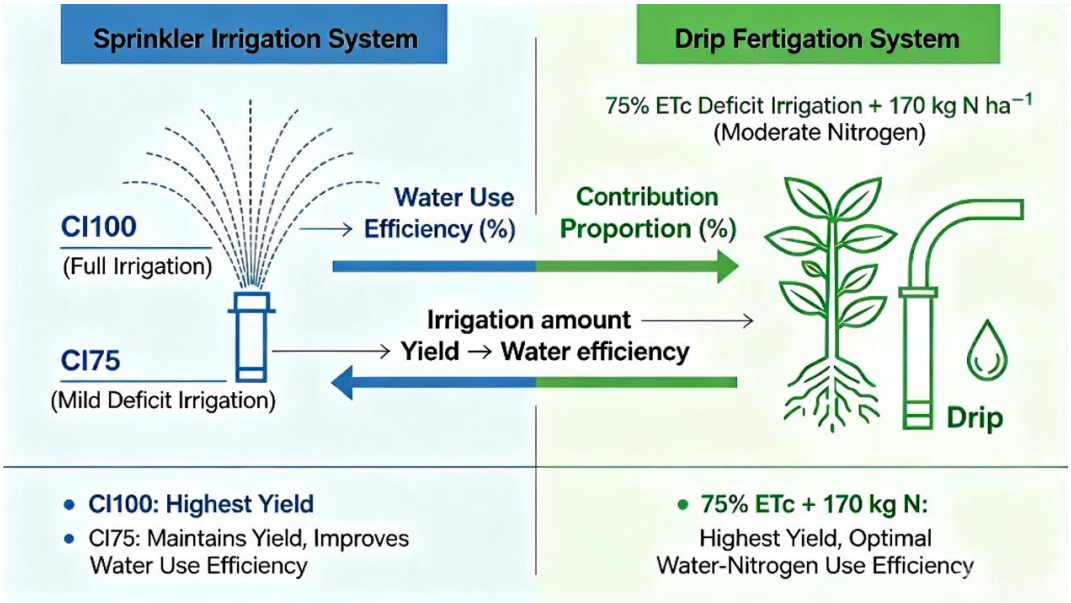

Figure 2 Comparative effects of sprinkler irrigation and drip-fertigated deficit irrigation on wheat grain yield and resource-use efficiency