However, intensive management also increases risks of groundwater depletion, nitrate leaching and greenhouse gas emissions if water and N exceed crop demand. In a long-term simulation-experiment framework, excess irrigation and N in wheat-maize rotations led to higher deep percolation and N leaching, requiring careful tuning of irrigation timing and total N to maintain yield while limiting losses (Xu et al., 2020). A global synthesis likewise highlighted that higher N doses, especially beyond 200 $kg \cdot ha^{-1}$, may reduce nitrogen use efficiency and aggravate environmental burdens, underscoring the need to balance productivity against resource and environmental costs in high-input systems (Wang et al., 2023).

8.2 Comparative analysis of water-saving and reduced-fertilizer production systems

Numerous field trials show that moderate reductions in irrigation and N can sustain or even enhance yield while improving resource use efficiency. Under spring wheat in Northwest China, reducing irrigation from 750 to 600 mm and N from 300 to 225 $kg \cdot ha^{-1}$ maintained dry-matter yield and increased grain yield by 12.9% in one year, while markedly improving water and N use efficiency and economic returns compared with farmers' higher-input practice (Kamran et al., 2023). Similarly, in a drip-irrigated system, deficit irrigation at 75% ETc combined with 170 $kg \cdot N \cdot ha^{-2}$ achieved the highest grain yield and water- and nitrogen-use efficiencies, with structural equation modeling indicating that N contributed over 65% of the yield gain relative to rainfed, unfertilized controls (Lu et al., 2021).

At system scale, alternative water-fertilizer-saving patterns can match conventional yields with lower inputs. In a four-year wheat-maize study in the North China Plain, supplemental drip irrigation at key stages plus 60% of recommended N (272 $kg \cdot ha^{-1}$ yr^{-1}) produced similar double-crop yields and net income to traditional surface irrigation with 453 $kg \cdot N \cdot ha^{-1}$ yr^{-1}, while increasing WUE, N use efficiency and reducing N loss (Li et al., 2023). A regional meta-analysis for the North China Plain further showed that deficit irrigation combined with optimized N splitting and partial organic substitution improved yield, N use efficiency and water use efficiency, with an optimal 7:3 inorganic-organic ratio under moderate irrigation (Wang et al., 2025).

8.3 Regional validation of ecologically adaptive cropping systems

Ecologically adaptive systems integrate crop diversification, conservation practices and input optimization to enhance yield stability and ecosystem services across regions. A review of eco-friendly wheat practices reported that low-input and organic systems generally reduce average yields relative to conventional, yet can deliver competitive and stable production when tailored to cultivar traits, soil agrochemistry and climate, especially under conservation tillage and diversified rotations (Rebouh et al., 2023). Long-term comparisons in Europe and North America illustrate this gradient: conventional systems averaged 6.96 t ha^{-1} with 163 kg mineral N, versus 5.94 t ha^{-1} under low-input and 4.15 t ha^{-1} under organic management, highlighting a clear yield-input trade-off that must be regionally calibrated.

More integrative regional assessments identify "positive deviant" systems that already combine high productivity with reduced environmental footprints. In wheat-maize double cropping on the North China Plain, 16% of surveyed farms were Pareto-optimal across seven sustainability indicators; these systems achieved 17% higher dietary energy output and 49% higher gross margins while lowering groundwater depletion, N loss and greenhouse gas emissions by roughly one-third to one-half compared with other farms (Liang et al., 2022). Key distinguishing practices included lower N in wheat, fewer irrigations, partial manure substitution and reduced pesticide use, demonstrating that regionally validated, ecologically adaptive prototypes can emerge from existing farmer practice rather than purely experimental designs.

9 Optimization Strategies and Regulatory Mechanisms for High-Yield Wheat Management

Studies on nitrogen timing and level show that yield components are highly plastic and can be steered through targeted fertilization regimes. Early and higher N inputs mainly increase grain number via more spikes, spikelets per spike and grains per spikelet, whereas delayed N tends to reduce grain number but increases grain weight, creating a managed trade-off between sink size and grain filling. The very large plasticity of grains per spike and grain number compared with grain weight suggests that management should first secure a high grain number and then avoid excessive late N that only increases grain size at the expense of total yield. Component-level analyses