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Statistical Analysis of Yield Components in Wheat under Different Management Practices

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Abstract Wheat yield formation is a complex physiological process jointly regulated by genetic traits, environmental conditions, and agricultural management practices. This study systematically investigates the effects of different management strategies on wheat yield components, including spike number, grains per spike, and thousand-grain weight. By integrating multiple management scenarios such as fertilization intensity, irrigation regimes, and planting density adjustments, the responses of yield formation processes were analyzed in terms of growth dynamics, component interactions, and regional variability. The results indicate that fertilization primarily influences spike development and grain setting, while water availability significantly regulates biomass accumulation and yield stability. Planting density further modulates population structure, leading to trade-offs among yield components. Significant coupling relationships were observed among spike number, grain number, and grain weight, suggesting a coordinated but competitive allocation mechanism. Statistical modeling revealed that management practices exert both direct and indirect effects on final yield through yield component mediation. Moreover, regional analysis highlights that climatic and soil conditions amplify or constrain management effectiveness. The findings provide a comprehensive understanding of how integrated agronomic practices shape wheat yield formation and offer theoretical support for optimizing high-yield and stable production systems under diverse agroecological conditions.

Keywords Wheat yield components; Management practices; Fertilization; Irrigation; Yield modeling

1 Introduction

Wheat is a major source of calories and protein worldwide, and further yield gains are essential to meet rising demand for food and feed. Grain yield in wheat is a complex quantitative trait shaped by genotype, environment, and their interaction, making direct selection on yield alone inefficient. A clearer understanding of yield components and how they respond to management practices is therefore critical for designing agronomic strategies and statistical models that improve both yield level and stability. This paper, "Statistical Analysis of Yield Components in Wheat under Different Management Practices," is positioned within this context. Wheat yield is typically decomposed into spike number per unit area, grain number per spike, and thousand-grain weight, with additional supporting traits such as biological yield and harvest index (Dolijanović et al., 2025). Numerous correlation and path-analysis studies show that grain yield is positively associated with spikes per area, grains per spike, and thousand-grain (or kernel) weight, as well as biological yield and harvest index (Choudhary et al., 2025). Path coefficient analyses repeatedly identify biological yield, grains per spike, and harvest index as having strong direct effects on grain yield, indicating their value as selection or diagnostic traits. Large multi-environment analyses further confirm that grains per unit area, determined by spike number and grains per spike, is the yield component most tightly linked to final yield (Slafer et al., 2022).

Agricultural management practices-especially fertilization, irrigation, tillage, sowing arrangement, and organic amendments-modify resource availability and crop environment, thereby altering yield components rather than yield directly. Meta-analyses and long-term trials show that integrating nitrogen management with irrigation, tillage, and organic inputs can increase wheat yield, nitrogen-use efficiency, and water-use efficiency relative to single-factor optimization. Conventional or well-structured tillage systems often improve grain weight per spike, thousand-grain weight, grain uniformity, and protein content compared with reduced or no-tillage systems, partly via effects on soil structure, weed pressure, and nutrient dynamics (Ahmadi et al., 2024). Sowing method and organic nutrient management (e.g., raised beds, split farmyard manure with liquid organics) can also enhance spike number, grain yield, and soil biological activity (Sharma et al., 2024). Fertilizer form and biostimulants (e.g., phosphorus, humic acids, mycorrhizae) further influence grains per spike, thousand-grain weight, biological yield, and harvest index, demonstrating multiple pathways from management to yield components and then to total grain yield.

Despite abundant evidence on individual factors, comparatively fewer studies jointly quantify how different management practices reshape the correlation structure and direct versus indirect effects among yield components. This motivates a statistical analysis of yield components in wheat under contrasting management regimes. The central research questions can be framed as: (i) How do key yield components (spikes per area, grains per spike, thousand-grain weight, biological yield, harvest index) respond to different management practices? (ii) How do management-induced changes in these components translate, via correlation and path relationships, into changes in grain yield? (iii) Do specific management practices strengthen the contribution of particular components (e.g., grains per spike or harvest index) to yield?

Based on prior correlation and path-analysis work, the study can hypothesize that: (1) management practices that enhance biological yield, spike number, grains per spike, and harvest index will significantly increase grain yield; (2) the relative importance of numerical components (spikes per area, grains per spike, thousand-grain weight) in determining yield will differ across management regimes; and (3) integrated or optimized management will not only raise yield but also modify the strength and direction of correlations among yield components, revealing management-specific yield-formation pathways. Statistical tools such as correlation, path analysis, and multivariate methods offer an appropriate framework to test these hypotheses and to identify the most responsive and yield-determining components under different management practices.

2 Regulatory Effects of Different Management Practices on Wheat Growth and Development

2.1 Effects of fertilization intensity on vegetative and reproductive growth

Nitrogen fertilization strongly modifies the hierarchy and plasticity of wheat yield components, with early-formed traits such as tiller and spike number responding differently from later traits like grain number and grain weight (Paolo et al., 2022). Increasing N rate up to about 150-300 $kg \cdot N \cdot ha^{-1}$ enhances grain number, grain weight, straw biomass, and plant height, although responses are curvilinear and context dependent (Yokamo et al., 2023). The timing of N also matters: delaying N from early tillering to stem elongation or later tends to reduce total yield but can increase grain weight, reflecting a trade-off between grain number and grain size.

Vegetative photosynthetic capacity and biomass accumulation are also sensitive to N intensity. Moderate to high N rates increase leaf area index, chlorophyll content, and flag-leaf photosynthesis, which in turn support higher total dry matter and reproductive organ biomass (Noor et al., 2023). Under partial shading, appropriate N can compensate for reduced light by boosting photosynthetic efficiency and dry matter transfer to ears, but under heavy shading, the regulatory effect of N on vegetative growth and yield formation becomes limited (Hongzhi et al., 2021). Meta-analysis shows that N use efficiency declines at high N and on fertile soils, implying that excessive fertilization may increase biomass but not proportionally increase grain yield.

2.2 Impacts of water availability on population structure regulation

Water supply around jointing and heading governs tiller survival and spike formation, thereby shaping population structure. Supplemental irrigation that wets the soil to 0-20 cm at jointing reduces tiller mortality, increases productive spike number, and improves leaf photosynthesis of both main stems and tillers, while deeper irrigation layers mainly increase transpiration and reduce water-use efficiency without clear yield gains (Shang et al., 2020). Deficit irrigation schemes that combine moderate water inputs with suitable planting patterns can raise tiller number, spikelets per spike, grains per spike, and radiation use efficiency, particularly when water is applied at both jointing and heading (Zhou et al., 2020).

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).

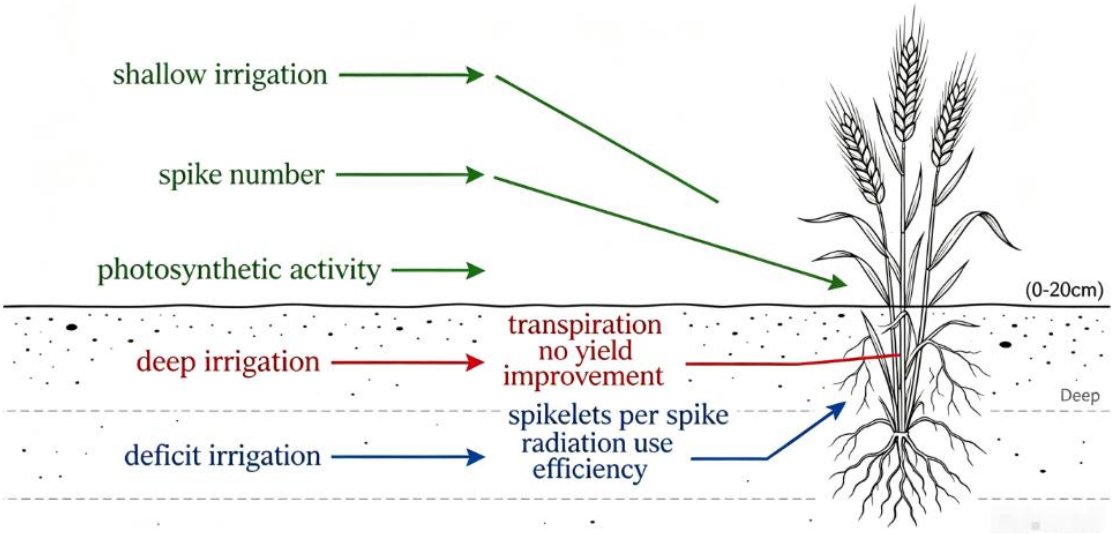

Figure 1 Mechanistic effects of irrigation depth and timing on tiller survival, spike formation, and yield component development in wheat

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 from tillers initiated early (from three-leaf stage to jointing), whereas late-initiated tillers produce few kernels and contribute minimally to yield (Tilley et al., 2019). The timing of tiller initiation and cessation, together with tiller mortality between jointing and anthesis, governs final spike density and explains large genotypic differences in spike number. Genetic variation in traits such as tillering onset, duration, and survival indicates substantial scope to manipulate these temporal patterns for yield improvement (Xie et al., 2015).

Temporal dynamics of tillering interact with canopy signals and resource competition. Low red:far-red light ratios arising as canopies close tend to accelerate the end of tillering and promote tiller abortion, thereby fixing spike number earlier in genotypes that are more sensitive to shading (Xie et al., 2015). Management and environment modify these dynamics by altering water status, radiation interception, and assimilate availability during the tillering window. Under post-jointing drought, ear-bearing capacity and seed setting of specific tiller positions are highly sensitive to the exact spike developmental stage at which stress occurs, with tillers at intermediate positions showing the greatest reductions in kernels per spike and grain yield per spike (Lin et al., 2020). These findings highlight that both the calendar time and developmental time at which stresses or inputs occur are critical in determining final spike number.

3.2 Limiting factors in grain number formation

Grain number per unit area is jointly determined by spike number and grains per spike, and both components follow a similar pattern of over-production of reproductive structures followed by intense abortion. Detailed observations of tiller and floret primordia show that survival, rather than initiation, is the primary driver of variation in spike number per area and grains per spike, especially during the late reproductive phase when degeneration is most intense (Bicego et al., 2024). Resource availability around stem elongation and heading strongly affects the survival of initiated tillers and florets, making grain number highly plastic in response to shading, thinning, and other changes in assimilate supply.

Within spikes, floret fertility and grain set are constrained by floral degradation and developmental timing. In hexaploid wheat, visible floral degradation from green-anther stage to anthesis strongly influences maximum floret primordia, fertile florets, and final grain number per spikelet, while detillering delays this degradation and increases the number of fertile florets and grains. The spatial gradient along the spike also reflects developmental limitations; basal spikelets are developmentally delayed and therefore exhibit higher floret abortion and more rudimentary spikelets, even when assimilate distribution along the spike is relatively uniform (Backhaus et al., 2023). Ovary size at anthesis emerges as a key integrative trait: larger ovaries, especially in distal florets, are associated with higher floret and grain survival, linking pre-anthesis growth with post-anthesis grain set (Guo et al., 2016).

3.3 Environmental response mechanisms of thousand-grain weight formation

Thousand-grain weight (TGW) is mainly determined during the grain filling period through the interplay between grain filling rate and duration. Field experiments manipulating post-anthesis night temperature show that warming of about 4 °C from 10 days after anthesis to maturity shortens the effective grain filling period, reducing TGW by roughly 3% per degree while leaving grain filling rate largely unchanged (Garcia et al., 2016). Similar work under controlled heat stress indicates that high temperatures hasten physiological maturity and decrease final grain weight, with genotypic differences in heat tolerance closely associated with the capacity to sustain a high grain filling rate (Dias and Lidon, 2009). These responses reflect sink-limited grain growth where accelerated development truncates the time over which potential grain size can be realized.

Broader analyses of climate-related factors confirm that elevated temperature and drought generally reduce grain yield of C3 cereals by depressing TGW. Meta-analysis shows that thousand-grain weight is particularly sensitive to warming, whereas drought and heat together can substantially reduce grain filling and starch accumulation even when grain number is less affected (Mariem et al., 2021). At the crop scale, variation in TGW can be explained by differences in post-anthesis thermal regime and radiation, as well as water availability that maintains photosynthesis and nitrogen metabolism during grain filling (Ru et al., 2023). New remote-sensing approaches, such as UAV-based estimation of grain filling rate and TGW from canopy traits, emphasize that TGW integrates 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).

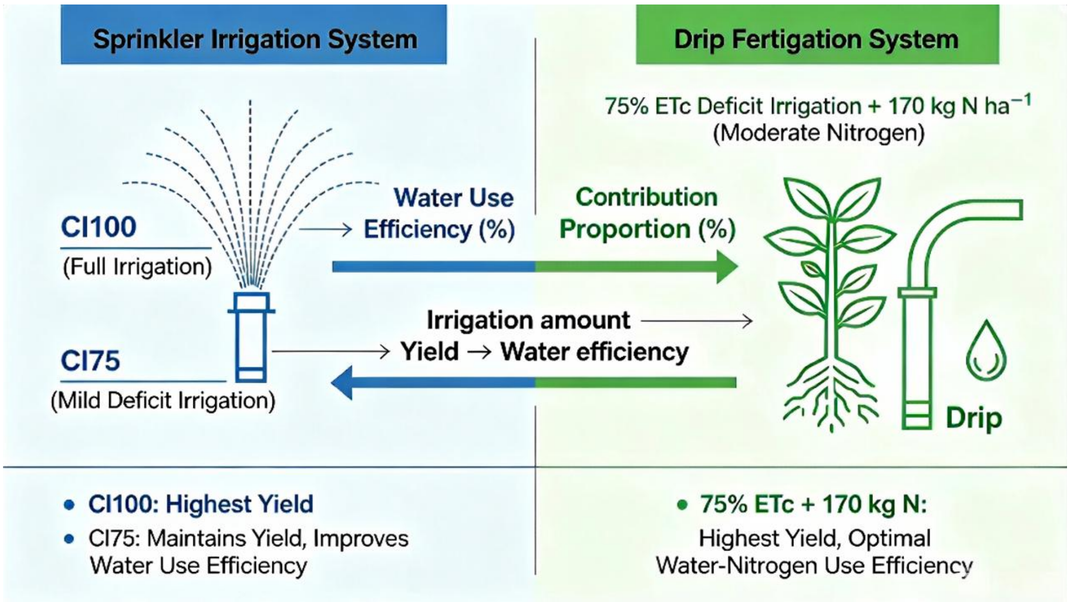

Figure 2 Comparative effects of sprinkler irrigation and drip-fertigated deficit irrigation on wheat grain yield and resource-use efficiency

4.3 Integrated effects of planting density and sowing date adjustment

Planting density and sowing date jointly shape yield by balancing spike number, grains per spike, and grain weight. In northeastern Poland, increasing sowing density from 200 to 400 live grains m^{-2} raised spikes·m^{-2} and grain yield, while delaying sowing by 14-28 days slightly reduced grains per spike but increased thousand-grain weight, with maximum yields achieved under mid-September to early October sowing and higher densities (Lachutta and Jankowski, 2024). A broader multi-genotype study found sowing date had a stronger impact on yield components than plant density, though density strongly correlated with heading time and tillering pattern (Kiss et al., 2018).

Fine-tuning density with N and sowing time can mitigate yield loss in sub-optimal windows. Under rice-wheat rotation, late sowing reduced spikes and kernels, but higher planting densities combined with a 25% N increase (300 kg·N·ha^{-1}) restored yield, with optimal densities depending on whether sowing was delayed 10 or 20 days (Tian et al., 2024). Other semi-winter wheat trials report that sowing around early-mid October at densities near 450×10^4 plants ha^{-1} maximizes yield, with higher densities mainly increasing spike number and lower densities favoring thousand-grain weight (Chen et al., 2021).

5 Coupling Relationships among Yield Components

5.1 Trade-off between spike number and grains per spike

The relationship between spike number per unit area and grains per spike is typically antagonistic, reflecting resource limitations during pre-anthesis development. Large multi-environment analyses show that increases in grains per·m^2 are usually achieved either via more spikes per·m^2 or more grains per spike, but simultaneous maximization of both components is rare (Xie and Sparkes, 2021). Compensation between these two routes appears as a hierarchy of plasticity, where spike number acts as a coarse regulator of grains per·m^2 and grains per spike fine-tune the response when resources or genotypes change.

Long-term trial data in winter wheat confirm that the strongest negative correlation among yield components often occurs between spike number and grains per spike, illustrating a robust trade-off in many environments. Yet cultivars differ in how strictly they follow this relationship; some lines deviate positively, combining relatively high spike number with high grains per spike and thus partially escaping compensation (Mandea et al., 2019). Recent work on grain number plasticity further suggests that overlapping developmental periods for tiller and floret mortality can generate feedback between spike number and grains per spike, so that resource shifts during stem elongation alter both components simultaneously (Bicego et al., 2024).

5.2 Synergistic and compensatory effects between grain number and grain weight

Across studies, grain yield is more tightly related to grains per·m^2 than to average grain weight, and negative correlations between grain number components and thousand-grain weight (TGW) are frequently reported. Genome-wide association in tetraploid wheat indicates that many loci for kernel number per spike (KNS) and TGW show opposing phenotypic effects, so gains in one component are often partially offset by losses in the other (Mangini et al., 2018). This genetic antagonism underpins the classic trade-off where increases in grain number reduce average grain size, limiting yield progress.

Nonetheless, both physiological and genetic evidence show that the trade-off is not absolute and can be mitigated. Doubled haploid populations derived from parents contrasting in grain number and weight have produced transgressive segregants with high grain number and relatively large grains, achieving very high yields and reducing the usual compensation. At the molecular level, some manipulations of expansin expression increased grain size without reducing grain number, boosting yield per spike and demonstrating that targeted modification of grain growth can overcome the typical negative association between grain number and grain weight in specific backgrounds (Calderini et al., 2020; Vicentin et al., 2024).

5.3 Mechanisms of multi-factor interactions affecting final yield

Final yield reflects not only pairwise trade-offs among components but also multi-factor interactions among management variables such as nitrogen, water, and density. Drip-fertigation experiments show that irrigation and nitrogen affect yield mainly through indirect effects on spike density, grains per spike, and TGW, with structural equation modeling confirming that both inputs operate via these components rather than directly on yield (Lu et al., 2021). Optimal combinations (e.g., deficit irrigation with moderate N) maximized grain yield and water-nitrogen use efficiency by increasing spike number and grains per spike while avoiding excessive reductions in grain weight.

More complex factorial trials combining planting pattern, supplementary irrigation, and plant density demonstrate significant three-way interactions on grain yield and resource-use efficiencies. Ridge-furrow planting with plastic mulch, moderate density, and limited supplemental irrigation increased grain yield and water productivity by improving soil water use, effective panicle number, and population N uptake, while maintaining a favorable balance between spike number and spike size (Dai et al., 2023). Other studies highlight that optimal density-nitrogen-water regimes improve spike number in upper and middle canopy layers and population uniformity, thereby enhancing biomass accumulation and yield at the population scale despite reduced per-stem grain weight at very high densities (Gao et al., 2025). These findings indicate that carefully tuned multi-factor management can exploit component plasticity, reduce deleterious trade-offs, and shift yield formation toward more synergistic combinations of grain number and grain weight.

6 Statistical Models and Yield Driving Mechanisms

6.1 Statistical characteristics of relationships between management practices and yield

Across contrasting environments, management practices such as nitrogen rate and irrigation schedule alter wheat yield primarily through effects on spike number, grain number per spike and grain weight. Under drought in Saudi Arabia, multivariate procedures identified spikes·m^{-2}, 100-grain weight, grain weight per spike and biological yield as the most influential variables for grain yield, highlighting how stress conditions sharpen the importance of key yield components (Leilah and Al-Khateeb, 2005). Under semi-arid conditions, variance analysis and regression likewise emphasized number of grains spike^{-1}, spikes·m^{-2} and thousand-kernel weight as main contributors to yield differences among durum genotypes (Frih et al., 2021).

Management-focused meta-analyses and field trials provide quantitative benchmarks for nitrogen-water interactions. A global synthesis showed that nitrogen addition increased wheat grain yield by about 15%, with 100-200 kg·N·ha^{-1} generally optimal for yield, protein and water productivity, and responses modulated by soil texture and climate. In the North China Plain, combined meta-analysis and short-term field experiments indicated that higher nitrogen rates with deficit irrigation improved yield, nitrogen use efficiency and water use efficiency, with an optimal 7:3 inorganic-organic fertilizer ratio under moderate irrigation.

6.2 Regression-based analysis of yield component drivers

Classical and stepwise regression consistently converge on a small set of yield drivers. Under drought, multiple linear and stepwise regressions showed that models including spikes·m^{-2}, grain number spike^{-1} and 100-grain weight explained up to ~93% of grain yield variation, underlining their dominant predictive value (Fouad, 2018). A semi-arid durum study similarly found that grains spike^{-1}, spikes·m^{-2} and thousand-kernel weight significantly explained yield variation in multiple and stepwise regression frameworks (Frih et al., 2021).

Recent work extends regression to farm-level management datasets. Using 22 agronomic and management traits from 90 farms, stepwise regression in Fars province selected nine variables-principally spikes·m^{-2}, grains spike^{-1} and thousand-grain weight, but also spike and awn traits, herbicide use, maturity time and soil salinity-as a parsimonious set, with partial least squares regression achieving $R^2 \approx 0.85$ using only these inputs (Behpouri et al., 2023). Under late-sown conditions, another regression study showed that seven traits (biological yield, harvest index, grain weight per spike, flag leaf length, main spike weight, spikelets per spike and grain appearance) explained ~98% of yield variability, underscoring the value of integrating both structural and physiological traits in yield forecasting (Solanki et al., 2024).

6.3 Multivariate integrated models and contribution decomposition

Multivariate approaches such as path analysis, factor analysis and PCA decompose direct and indirect contributions of components to yield. In bread wheat, path analysis frequently reveals strong direct effects of spike weight and thousand-kernel weight on grain yield, with grain filling rate and spike number exerting important indirect effects, suggesting these as efficient selection and management targets (Matković-Stojšin et al., 2018; Elmassry and Shal, 2020). Another path-analytic study found that spikelet number and thousand-seed weight, followed by grain size and grain number spike^{-1}, had the largest direct impacts on yield, while multicollinearity diagnostics confirmed that treating all traits as first-order predictors was statistically valid.

Integrated multivariate models have also been used under specific management and climate scenarios. Under drought, combining factor analysis, regression, PCA and clustering confirmed that spikes·m^{-2}, 100-grain weight, grain weight per spike and biological yield form a core determinant set for yield, with these variables loading heavily on principal components associated with productivity (Leilah and Al-Khateeb, 2005). In a Mediterranean irrigation-nitrogen trial, factor analysis grouped variables into yield/water use, yield components and quality factors, while stepwise multivariate regression showed that water footprint indices could be well predicted from NDVI measured at key growth stages, linking spectral signals to integrated yield and resource-use outcomes under different irrigation and nitrogen strategies (Tomaz et al., 2021).

7 Regional Variation in Yield Response Characteristics

7.1 Differences in management responses across climatic zones

Wheat yield responses to management vary strongly among climatic zones because temperature, precipitation, and radiation contribute differently to yield variation across regions. In China, combined changes in mean temperature, precipitation, and solar radiation explain substantial regional differences in yield, with radiation and precipitation often being the dominant drivers and their joint effects exceeding those of any single factor (Han et al., 2023). Similar regional patterns emerge when extreme temperature indicators are used: extreme growing-degree days and other thermal indices cause larger proportional yield losses in northern and spring-wheat regions than in southern winter-wheat zones, even when precipitation increases (Han et al., 2025).

Management practices modify these climate-driven patterns and partially buffer yield gaps. In Mediterranean and MENA agro-ecological zones, simulations show that optimal supplemental irrigation and nitrogen rates, together with adjusted sowing dates, can raise attainable yields by 30-50% and improve water productivity by up to 70%, despite projected 18-30% climate-induced yield declines (Tita et al., 2025). On-farm analyses in the U.S. central Great Plains further reveal that regional clustering by climate is needed, because fertilizer management (N, P, S), fungicide use, and cultivar choice interact with local weather to determine realized yield and yield gaps (Jaenisch et al., 2021).

7.2 Regulatory effects of soil types on yield formation

Soil physical and chemical properties exert strong regulatory effects on wheat yield components and yield gaps. At field scale, small-scale variation in soil texture and organic carbon in both topsoil and subsoil explains nearly half of the spatial variability in grain yield and key components such as tiller density, with higher clay in topsoil enhancing yield but higher clay in subsoil reducing it (Groß et al., 2023). Across arid and semi-arid fields, soil organic carbon, total nitrogen, and available potassium are positively associated with grain number, spike traits, plant height, and both economic and biological yields, indicating that improved physicochemical status narrows yield gaps (Bagheripour et al., 2024).

Management inputs that change soil structure and organic matter further regulate yield formation. A global meta-analysis shows that increasing soil organic carbon up to about 2% is generally associated with higher wheat yields, with diminishing returns beyond this threshold and substantial potential to reduce nitrogen fertilizer needs where SOC is currently low (Oldfield et al., 2018). At plot scale, adding organic residues such as composted bagasse, manure, or straw improves aggregate stability, infiltration, and bulk density, leading to progressive increases in grain and stubble yields as application rates rise (Barzegar et al., 2002).

7.3 Stability comparison under varying hydrothermal conditions

Hydrothermal variability-interacting heat and water conditions-strongly shapes yield stability, with marked genotype × environment interactions. Multi-environment trials under irrigated, drought, and heat-stress conditions show significant variance for genotype, environment, and their interaction, and AMMI/GGE analyses identify specific genotypes that win in irrigated, drought, or heat environments, as well as a subset that combines high mean yield with broad stability across all stress scenarios (Ram et al., 2020). Similar AMMI/GGE analyses in irrigated versus terminal heat-stress environments indicate that some elite lines are specifically adapted to heat, while others show both above-average yield and high stability across contrasting moisture and temperature regimes.

Beyond individual trials, site conditions determine the magnitude of hydrothermal yield penalties. In Germany, combined heat-drought indices during the reproductive phase have the highest explanatory power for yield loss, with poor sites (low soil quality, lower precipitation) suffering two- to three-fold larger reductions than high-quality, high-rainfall locations under comparable stress (Riedesel et al., 2024). Meta-environment analyses of bread and durum wheat under normal, heat, and drought conditions also reveal complex genotype responses in quality traits and micronutrients, yet identify genotypes that maintain yield and nutritional stability across stress environments.

Across climatic zones, management responses in wheat are tightly conditioned by regional temperature, radiation, and precipitation regimes, with optimized water-nutrient-sowing strategies substantially narrowing yield gaps. Soil type and its physicochemical status regulate yield formation by controlling yield components and mediating the benefits of management inputs and organic amendments. Under varying hydrothermal conditions, both genotype choice and site quality govern yield stability, emphasizing the need to combine statistical G×E analysis with site-specific soil and climate information when designing management practices.

8 Case Study: Comparative Analysis of Typical Management Systems on Yield Structure

8.1 Characteristics of high-input intensive management systems

High-input intensive wheat systems are typically defined by full irrigation and relatively high nitrogen (N) rates, designed to maximize grain yield, grain protein and water productivity. Global and regional meta-analyses show that N addition generally increases grain yield by about 15% and water productivity by around 10%, with optimal responses often at 100-200 $kg\cdot N\cdot ha^{-1}$ under humid or irrigated conditions (Wang et al., 2023). In arid zones with drip or micro-sprinkler irrigation, full evapotranspiration replacement combined with high N rates (e.g., 238 $kg\cdot N\cdot ha^{-1}$) increased grain yield, biological yield and seed index, and raised crop water productivity by more than 20% relative to lower N inputs (Figure 3) (Abdelrhman et al., 2025).

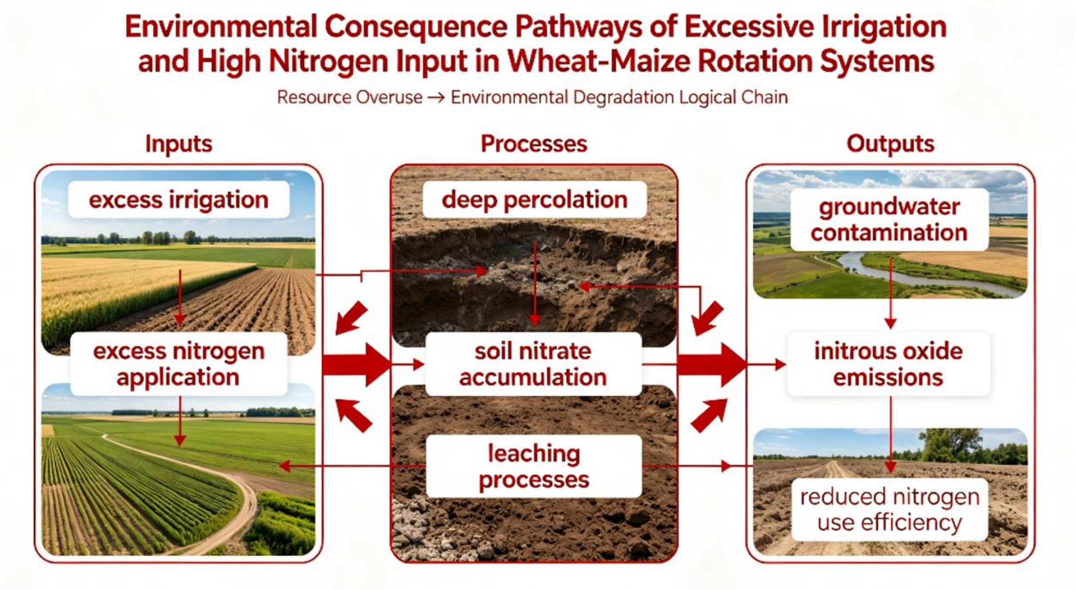

Figure 3 Environmental consequence pathways of excessive irrigation and nitrogen inputs in wheat-based cropping systems, highlighting leaching, groundwater depletion and greenhouse gas emissions

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·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·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·N·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·ha^{-1} yr^{-1}) produced similar double-crop yields and net income to traditional surface irrigation with 453 kg·N·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 under different water-N and cultivation modes further clarify thresholds for optimizing spike number and grains per spike. In the Huang-Huai Plain, yields below about 7.5 t ha^{-1} depend on jointly increasing spike number and grains per spike, while higher yields rely mainly on further increasing grains per spike through rapid pre-anthesis dry-matter accumulation. Both spike and non-spike dry matter and nitrogen before anthesis show strong positive relationships with grains per spike, whereas excessive N allocation to spikes reduces grain number, indicating that balanced N distribution between spike and vegetative organs is critical for optimizing the main yield component.

Water-nitrogen combinations create strong synergies in both production and resource-use traits. On the North China Plain, factorial irrigation-N experiments showed that both inputs increased total water use, but also intensified water consumption during grain filling and enhanced soil water use, with a clear positive synergy between crop water productivity and nitrogen-use efficiency across treatments. Decomposing nitrogen-use efficiency revealed that this synergy was driven mainly by higher nitrogen uptake efficiency rather than utilization efficiency, particularly where irrigation increased both pre- and post-anthesis N assimilation into grain. Similar interaction mechanisms appear under more complex management matrices that include planting pattern and density. In a semi-humid but drought-prone region, ridge-furrow planting with plastic film, moderate supplementary irrigation, and medium plant density significantly improved grain yield, water productivity, agronomic N-use efficiency and net income compared with flat planting or sub-optimal densities. These effects arose from interactive gains in soil water consumption, population N uptake and effective panicle number per unit area, demonstrating that coordinated adjustment of canopy structure and soil water capture can synchronize water and N supply with the formation of spikes and grains.

Long-term integrated management strategies illustrate how multiple levers can be combined into robust high-yield systems. In North China, integrated soil and crop system management that delayed sowing, increased seeding rate and optimized fertilization and irrigation achieved yields within about 4-5% of an input-intensive “high-yield” treatment, while markedly increasing nitrogen-use efficiency, water productivity and N balance. A related strategy using higher seeding rate, slightly delayed sowing and re-timed N topdressing similarly produced yields close to the maximum treatment but with much higher NUE and net profit, indicating that coordinated adjustment of sowing date, plant density and N partitioning can support both high yield and economic efficiency. At regional and systems scales, integrated crop management (ICM) and eco-friendly practices provide a broader template for stable high production. Global evidence shows that ICM can raise wheat yields by roughly 16-30% through site-specific nutrient management, conservation tillage, and complementary pest and disease control, while reducing excessive N use and environmental risk. Reviews of eco-friendly wheat systems further emphasize that stable high yields require normative strategies that jointly consider cultivar traits, crop rotation, reduced tillage, biological protection and soil agrochemical status, so that management buffers climatic variability while sustaining yield components across seasons.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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