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