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