Process-based rice models such as ORYZA and APSIM-Oryza have been widely used to simulate phenology, biomass accumulation, and grain yield across diverse environments and management scenarios. These ecophysiological models dynamically represent photosynthesis, development, and soil water balance, and have been extended to include responses to drought and salinity, achieving yield root mean square errors generally within experimental uncertainty across stress gradients (Chang et al., 2023). More recently, mechanistic models of grain filling have been developed that explicitly link leaf-level photosynthesis, whole-plant carbon-nitrogen interactions, and panicle sink dynamics, reproducing observed yield formation under varied environmental and genetic perturbations and identifying stability of grain filling rate as a key determinant of maximum yield. Nonetheless, model evaluations indicate that conventional formulations often underperform when simulating yield responses to low-temperature stress or high-temperature-induced sterility at multiple stages, highlighting the need for improved temperature response functions that are stage-specific and variety-dependent (Shrestha et al., 2022; Shi et al., 2024).

The objective of this study is to develop and evaluate a modeling framework for grain yield formation in rice that explicitly couples temperature stress responses with water management effects across key developmental stages. Building on established process-based models, the approach refines algorithms for spikelet fertility, grain number per panicle, and grain filling under low and high temperatures, while incorporating contrasting irrigation regimes representative of traditional flooding and water-saving practices. The scope of the study includes calibration and validation using multi-environment experimental datasets, sensitivity analysis to identify dominant climatic and management drivers, and scenario simulations to quantify yield risks and opportunities under projected warming and alternative water regimes. By integrating temperature and water processes at the level of yield components, the work aims to provide a more reliable tool for assessing adaptation strategies-such as adjusted planting dates, stress-tolerant varieties, and optimized irrigation-for sustaining rice production and water productivity in a changing climate.

2 Physiological Basis of Rice Yield Formation

2.1 Growth stages and yield components of rice

The rice growth cycle is commonly divided into vegetative, reproductive, and grain-filling (ripening) stages, each with characteristic organs and yield-related processes. During vegetative growth, plant height, root development, leaf area, and especially tillering determine the potential panicle number per unit area and thus set the primary framework for yield. In the reproductive stage, panicle development, booting, and flowering occur; here the number of spikelets per panicle is defined, and this stage is the most sensitive to biotic and abiotic stresses, including temperature extremes.

Grain filling and ripening determine spikelet weight through endosperm development and carbohydrate deposition, with asynchronous filling between superior and inferior spikelets often limiting full yield potential (Liu et al., 2025). Yield analyses across diverse varieties show that total spikelet number (a function of panicle number and spikelets per panicle) correlates strongly and positively with grain yield, while higher spikelet numbers can trade off with filled grain percentage and grain weight if sink capacity exceeds source supply (Liu et al., 2024). Thus, yield modeling must capture how growth stages sequentially define panicle number, spikelet number, spikelet fertility, and grain weight.

2.2 Effects of temperature on rice physiology

Rice is highly sensitive to temperature, particularly during reproductive and grain-filling stages, where both high day temperatures and high night temperatures reduce yield through impaired reproductive development and altered carbon balance (El-Mageed et al., 2022; Shrestha et al., 2022). Heat stress at panicle initiation diminishes spikelet number by attenuating secondary branch and floret differentiation and enhancing degradation, while later heat episodes mainly affect spikelet fertility and grain weight, emphasizing the need for stage-resolved temperature response functions in models.

At flowering and grain filling, high temperatures increase spikelet sterility and reduce grain weight via multiple morpho-physiological pathways, including distortion of floral organs, reduced pollen viability, impaired anther