yield-formation models support evaluation of irrigation as an adaptation option (Baydar, 2026). In Central Java, coupling MarkSim-generated weather with CERES-Rice projected yield decreases in all seasons under RCP2.6-8.5, with up to 11.8% reduction in the second dry season, and pointed to dynamic cropping calendars, irrigation modernization, and integrated nutrient management as priority adaptations (Ansari et al., 2021).

Meta-analytic and multi-model frameworks extend these assessments to global and regional risk profiles. A global meta-model derived from 8,703 process-model simulations showed that, under RCP4.5 without adaptation, major crops including rice face mean yield losses of 6%-21%, but that cultivar choice for rice and irrigation method for maize are among the most influential adaptive strategies, partially offsetting losses as warming intensifies (Abramoff et al., 2023). A separate meta-analysis of 111 climate-rice modeling studies quantified that each 1 °C increase in mean temperature reduces rice yield by 3.85% on average, while elevated $CO_2$ and adaptive management can compensate some losses, underscoring the role of yield models in probabilistic risk assessment and in designing adaptation portfolios (Li et al., 2024).

### 6.3 Precision Agriculture and Digital Farming

Yield formation models are increasingly embedded in precision agriculture systems that combine remote sensing, IoT, and AI to support within-field management. An integrated IoT-based framework uses multispectral satellite indices, machine-learning yield prediction (random forest $R^2 \approx 0.96$), and fuzzy-logic irrigation control to recommend suitable crops and fertilizer, while a solar-powered irrigation system achieves about 61% water savings compared with average logic, demonstrating how digital decision layers can operationalize model insights on crop water and nutrient requirements (Saha et al., 2025). At a broader scale, reviews of remote-sensing applications in precision agriculture highlight how satellite and UAV data, linked to crop growth and yield models, are now used operationally for crop monitoring, irrigation scheduling, variable-rate nutrient application, and yield prediction, supported by cloud computing and machine learning workflows (Sishodia et al., 2020).

Recent syntheses of IoT- and AI-enabled sensing technologies emphasize that dense soil-moisture, nutrient, and plant-stress sensor networks, combined with models and ML (e.g., SVMs, CNNs, random forests), underpin real-time optimization of irrigation, fertilization, and pest management across arable systems (Miller et al., 2025). Complementary reviews of precision agriculture for yield prediction stress that hybrid systems merging deep learning (e.g., Bi-LSTM) with multisource remote-sensing inputs can capture the combined effects of temperature, water status, and other stresses on yield, pointing toward digital twins of rice cropping systems where grain yield formation under variable temperature and water regimes is continuously simulated and updated from field data (Saha et al., 2025).

## 7 Case Study: Modeling Rice Yield Under Alternate Wetting and Drying Irrigation

### 7.1 Experimental design and data collection

Field experiments comparing alternate wetting and drying (AWD) with continuous flooding (CF) typically use side-by-side plots differing only in water regime, enabling quantification of yield and water responses across soils, climates, and management practices. A global meta-analysis synthesized 56 such studies (528 paired comparisons) and defined mild AWD using thresholds of soil water potential ≥ -20 kPa or field water level not dropping below 15 cm, and severe AWD when soils dried beyond -20 kPa, with associated measurements of yield, water inputs, and basic soil properties. More recent meta-analyses have expanded this database, assembling thousands of observations worldwide and characterizing AWD treatments by water potential and water-level thresholds together with soil organic carbon, pH, and nitrate to link yield outcomes with edaphic changes (Zhou et al., 2025).

Experimental designs used for model calibration and testing often include multiple irrigation schemes and long weather records. In China, a two-year field trial with four irrigation and drainage treatments-AWD, controlled drainage, and two controlled irrigation-drainage regimes-was established to calibrate CERES-Rice using detailed measurements of grain yield, biomass, leaf area index, evapotranspiration, irrigation volume, and ponded water depth. Long-term simulations then combined these calibrated parameters with 60 years of meteorological data classified into wet, normal, and dry years to evaluate yield and water-use efficiency trade-offs among AWD and alternative schemes (Gao et al., 2023).