Future modeling must better integrate climate, hydrology, and crop growth, particularly in data-scarce, climate-vulnerable regions. A review of climate-hydrological-crop modeling for Indonesian rice production highlighted critical gaps in long-term observations, local cultivar data, and systematic calibration/validation, as well as limited use of fully coupled multi-model frameworks. Bayesian multi-model ensemble methods applied to Chinese rice regions showed that statistically combining multiple climate models can reduce bias in temperature, radiation, and wind projections and provide more robust estimates of future yield, evapotranspiration, and irrigation requirements. There is also strong scope for hybrid approaches linking process-based models with machine learning and explainable AI. A recent study in China coupled DSSAT with random forests and SHAP analysis to project rice yields under multiple SSP scenarios and to rank the relative influence of variables such as growing degree days, shallow versus deep soil moisture, and precipitation regimes on yield. Global meta-modeling across 8,703 process-model simulations similarly used machine learning to map yield change as a function of climate and adaptation, revealing that for rice, cultivar choice is a dominant lever for avoiding large losses, and demonstrating how statistical emulators can synthesize complex multi-model ensembles for risk analysis.

Rice yield formation under changing temperature and water regimes is governed by interacting physiological processes and management decisions that are only partially resolved in current models. Meta-analyses show that rising temperature and altered precipitation generally reduce rice yields, but that elevated CO_2 and adaptive practices, including improved management, can offset part of these losses; however, the magnitude and direction of impacts vary widely across models and regions. Probabilistic assessments and global meta-models further indicate that without adaptation, most rice-growing areas face significant yield declines as global mean temperature rises, while adaptation-particularly through cultivar choice and irrigation strategies-substantially narrows projected losses. Going forward, credible prediction and decision support will require to reduce structural and parametric uncertainty in ecophysiological models; embedding them in integrated climate-hydrological-crop frameworks; and exploiting machine learning and ensemble techniques to quantify risk and design robust adaptation portfolios. By explicitly representing temperature and water interactions, and by using improved data and hybrid modeling strategies, next-generation rice yield models can more reliably guide climate-smart water management, cultivar deployment, and policy for sustainable rice production under a warming and water-constrained climate.

Acknowledgments

Thanks to the reviewers for providing detailed comments and guidance on the manuscript of this study. The reviewers' keen insights into the issues and attention to detail have greatly benefited the authors.

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.

References

Abramoff R., Ciais P., Zhu P., Hasegawa T., Wakatsuki H., and Makowski D., 2023, Adaptation strategies strongly reduce the future impacts of climate change on simulated crop yields, Earth's Future, 11(3): e2022EF003190.
https://doi.org/10.1029/2022EF003190

Ansari A., Lin Y., and Lur H., 2021, Evaluating and adapting climate change impacts on rice production in Indonesia: A case study of the Keduang Subwatershed, Central Java, Environments, 8(11): 117.
https://doi.org/10.3390/environments8110117

Arumugam P., Chemura A., Schauberger B., and Gornott C., 2020, Near real-time biophysical rice (*Oryza sativa* L.) yield estimation to support crop insurance implementation in India, Agronomy, 10(11): 1674.
https://doi.org/10.3390/agronomy10111674

Baydar A., 2026, Assessing rice yield responses to climate change scenarios using a crop simulation model, PeerJ, 14: e20965.
https://doi.org/10.7717/peerj.20965

Bo Y., Wang X., Van Groenigen K., Linquist B., Müller C., Li T., Yang J., Jägermeyr J., Qin Y., and Zhou F., 2024, Improved alternate wetting and drying irrigation increases global water productivity, Nature Food, 5(12): 1005-1013.
https://doi.org/10.1038/s43016-024-01081-z