absorb in-season observations from weather and remote sensing to update expected yield and risk. For dryland sorghum systems facing increasing climate variability, this kind of staged decision support may matter as much as any single new trait. (Jabed and Murad, 2024; Mihret et al., 2024).

7.4 Improving Yield Modeling Through Emerging Technologies

The next step in sorghum yield modeling is not simply "more AI." It is better integration across scales. Emerging work already points in that direction: UAV and satellite remote sensing add frequent canopy observations, machine learning improves pattern detection, and process-based models provide biological structure. Phenotyping, explainable AI, and genotype-aware modeling can make this integration more useful rather than merely more complex. Particularly promising are hybrid frameworks in which a crop model provides stage structure and water-balance logic, while data-driven methods update parameters or correct prediction error using contemporary observations. This may be the most realistic way to improve sorghum yield prediction under rapidly changing climates, because it preserves interpretability while benefiting from rich data streams. The most valuable future systems will likely be those that can explain why a yield prediction changed, not only produce a more accurate number (Figure 3) (Jabed and Murad, 2024; Deng et al., 2025; Karongo et al., 2025).

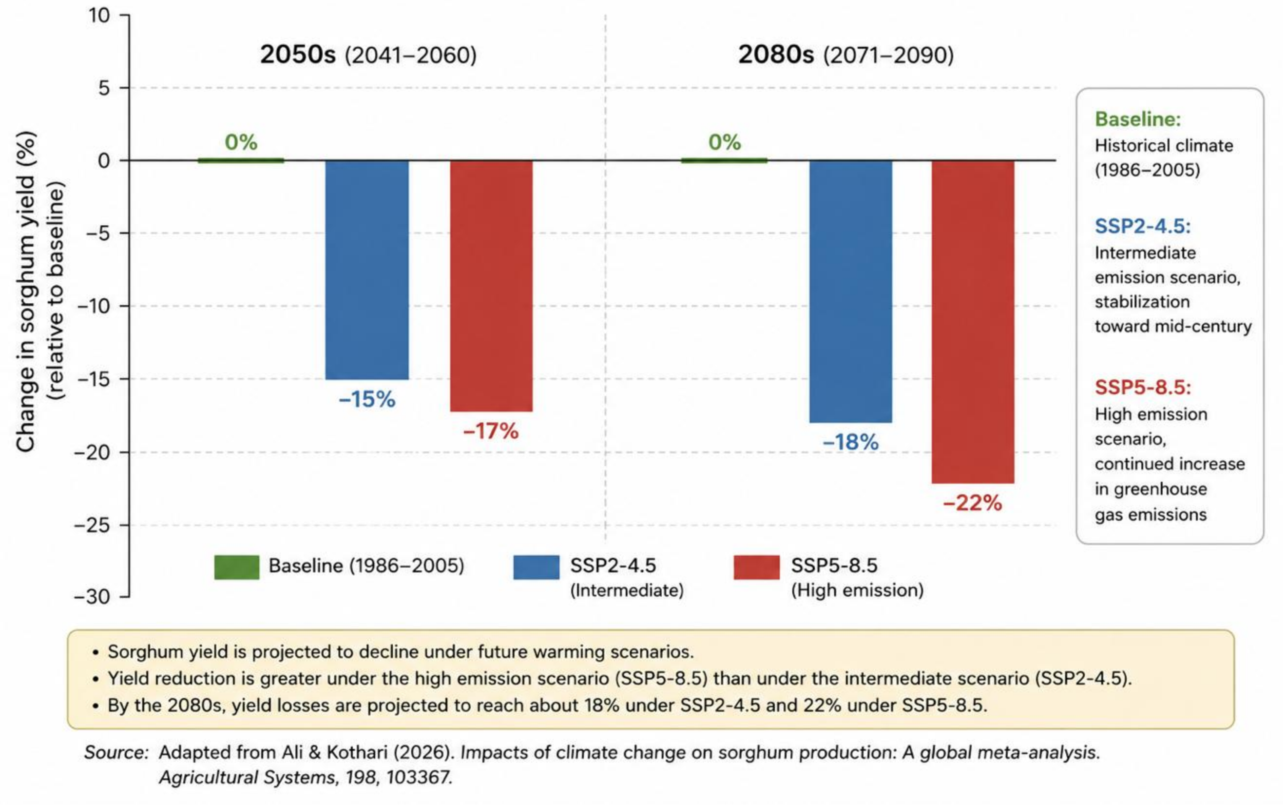

Figure 3 Integrated framework for next-generation sorghum yield prediction

8 Conclusions and Future Perspectives

This study argues that sorghum yield formation cannot be understood, or modeled well, by treating temperature and rainfall as broad background variables. Their impact depends on developmental timing, stress duration, and interaction. Temperature drives phenology and can damage reproduction directly, while rainfall determines whether the crop can sustain the physiological processes that support grain set and grain filling. Reproductive-stage heat, post-flowering drought, and poorly distributed rainfall are repeatedly identified as the most consequential threats to stable yield. At the modeling level, empirical, process-based, remote-sensing, and machine-learning approaches all contribute something important, but their real value is highest when they are combined rather than isolated.