A useful sorghum model must therefore represent not just total biomass, but how climate shapes the component pathway to yield (Baye et al., 2022; Otwani et al., 2025).

2.3 Physiological processes related to yield formation

Behind those yield components lie a set of physiological processes that climate directly modifies. Photosynthesis supplies assimilates for canopy growth, reproduction, and grain filling. Stomatal conductance and plant hydraulics regulate the trade-off between carbon uptake and water loss. Assimilate partitioning determines whether biomass supports stems, leaves, roots, or grain at a given stage. Under water stress, sorghum often maintains function better than many cereals through deep rooting, osmotic adjustment, partial stomatal control, and a capacity in some genotypes to conserve photosynthetic performance even when water becomes limiting. Recent physiological work has shown meaningful genotypic variation in intrinsic water-use efficiency and associated hydraulic traits, with improved water-use efficiency in some genotypes arising not only from stronger stomatal restriction but from better maintenance of photosynthetic capacity under stress. That is especially important for modeling because it means drought tolerance cannot be treated as a single trait or a single reduction factor. It emerges from interacting physiological controls that differ by genotype and stage (Ndlovu et al., 2021; Prasad et al., 2021; Al-Salman et al., 2024).

2.4 Environmental sensitivity across growth stages

Not all growth stages are equally vulnerable (Figure 1). The literature repeatedly shows that reproductive stages are more sensitive than vegetative stages, although early establishment can also be critical where emergence stress is severe. In sorghum, the period from panicle emergence through anthesis is especially important because it governs floret fertility, pollen development, fertilization, and embryo formation. Later, grain filling becomes the decisive stage for grain size and final grain mass. Water stress or heat stress during these windows can lower yield even when earlier biomass production looked satisfactory. The stage-specific nature of stress is one reason the same seasonal rainfall or seasonal mean temperature can produce very different outcomes in different years: what matters is where stress lands in relation to developmental timing. For modelers, that means stage-based sensitivity functions are not optional details. They are the bridge between weather time series and harvest outcomes (Prasad et al., 2015; Prasad et al., 2021; Smith et al., 2023).

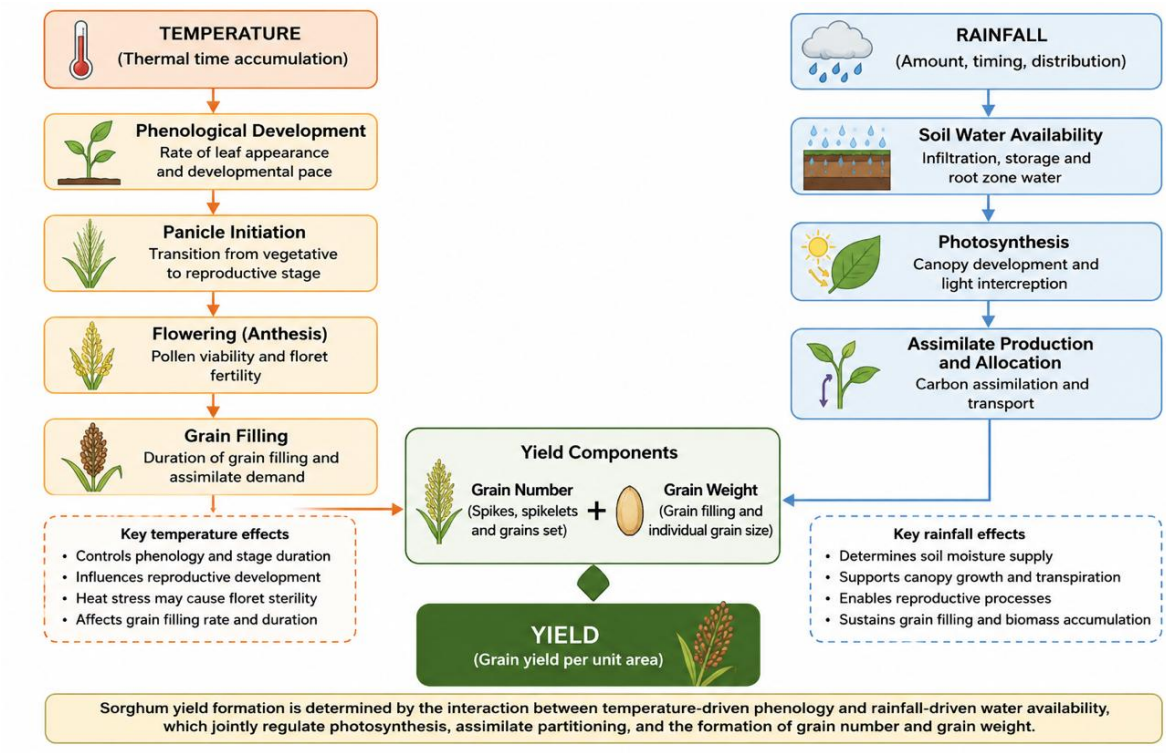

Figure 1 Biological and physiological framework of sorghum yield formation