averages; they focus instead on monthly, event-based, or growth-stage-specific conditions (Kumar et al., 2009; Prasad et al., 2021; Tolosa et al., 2023).

Climate-based yield modeling in sorghum has moved through several phases. Early work relied mainly on correlation and regression, asking which combinations of rainfall totals, rainy days, or seasonal temperatures tracked annual yield variation. That approach remains useful where data are sparse and decisions must be made quickly. More recent work has added process-based models such as APSIM, DSSAT-CERES-Sorghum, and AquaCrop, which represent phenology, biomass accumulation, water balance, and grain formation mechanistically. In parallel, remote sensing and machine learning have expanded the modeling toolbox by making it possible to estimate yield from canopy signals, spatial heterogeneity, and multi-source environmental data. The result is not a single dominant method, but an increasingly layered modeling landscape in which empirical, mechanistic, and data-driven approaches are used for different purposes. For a review aimed at a computationally oriented journal, that diversity is especially important: the field is moving toward hybrid systems that use biology to structure models and data science to improve scale, speed, and prediction accuracy (Tirfessa et al., 2023; Jabed and Murad, 2024; Gardi et al., 2025).

This study has four linked objectives. First, it summarizes the biological and physiological basis of sorghum yield formation in a form that is clear enough to support modeling decisions. Second, it examines how temperature and rainfall affect yield formation directly and through heat stress, drought stress, and their interaction. Third, it compares the main modeling approaches now used for sorghum yield prediction, not to declare a single winner, but to clarify what each method captures well and where each remains limited. Fourth, it uses published case evidence from semi-arid regions to show how climate-yield relationships work in practice and what that means for adaptation and management. The review is deliberately written as a synthesis rather than a report of new experimental data, so its contribution lies in organizing established evidence into a coherent framework that can support both research design and practical decision-making.

2 Biological and Physiological Basis of Sorghum Yield Formation

2.1 Growth and development characteristics of sorghum

Sorghum is a C4 cereal with strong adaptation to hot, high-radiation environments, and its development is usually described through discrete vegetative and reproductive stages linked to thermal time. That developmental structure matters because the crop does not respond to weather uniformly across the whole season. The timing of panicle initiation, flowering, and maturity depends on genotype, temperature, and in many materials photoperiod sensitivity; together, those factors determine whether the crop escapes or encounters stress at key points. Modeling work on diverse sorghum genotypes has shown that accurate prediction of phenology and canopy development requires explicit representation of temperature and photoperiod responses rather than broad maturity labels alone. This has two practical implications. First, cultivars that appear similar in duration can behave differently under shifting sowing dates or altered season length. Second, any serious attempt to model yield formation from climate must begin with phenology, because an error in stage timing usually propagates into errors in stress exposure, biomass partitioning, and grain yield (Tirfessa et al., 2023).

2.2 Major yield components

Sorghum grain yield is built from a small set of components, but the timing of their determination is staggered across the season. Grain number and grain weight are the dominant immediate components, while panicle size, floret fertility, seed set, and tiller contribution help explain how those two primary components are assembled. The number of kernels is largely determined during the earlier reproductive period, especially from panicle initiation through flowering and early fertilization, whereas kernel weight depends more strongly on post-flowering assimilate supply and the duration and quality of grain filling. That distinction matters for climate analysis because temperature and rainfall do not affect all components in the same way. Heat or water deficit around flowering tends to depress grain number, while post-flowering stress more often reduces individual grain weight. Genetic studies also reach the same broader conclusion from a different angle: grain size, grain number per panicle, and grain weight are central yield-related traits, but they are interconnected and subject to trade-offs.